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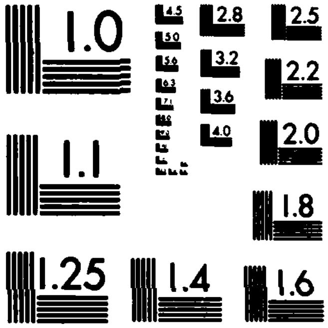

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HIGH STRENGTH, LONG LENGTH OPTICAL FIBERS

AD-A132 909

INCREASED DURABILITY OF OPTICAL FIBER THROUGH THE USE OF COMPRESSIVE CLADDING

FINAL TECHNICAL REPORT

12 DECEMBER 1978 TO 12 JUNE 1980

CONTRACT N00123-79-C-0301

PREPARED FOR:

NAVAL OCEAN SYSTEMS CENTER
271 CATALINA BOULEVARD
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HIGH STRENGTH, LONG LENGTH OPTICAL FIBERS

Increased Durability of Optical Fiber Through the Use of Compressive Cladding

FINAL TECHNICAL REPORT
12 December 1978-12 June 1980
Contract N00123-79-C-0301

Prepared for:

Naval Ocean Systems Center
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The durability of optical fiber waveguides has been improved by employing a surface compressive cladding technique. The durable fibers having a very thin surface compressive layer of either pure silica or Ti-doped silica were fabricated based on the developed computer models of the three-layer and the four-layer structure fibers. Surface compressive stresses greater than 100 kpsi (0.69 GPa) were deduced from the static fatigue and bend test results of the fibers having higher thermal expansion coefficients in inner layers with a thin Ti-doped silica surface layer.

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1.0 INTRODUCTION

Long length, high strength, low loss optical fibers are now being routinely fabricated through the careful controlling of process fabrication parameters. However, one of the key problems associated with the application of optical fibers is the degradation of their high strength properties. The degradation in strength usually occurs when the silica fibers are subjected, in the presence of moisture, to a load for an extended period of time. This phenomenon is known as stress corrosion or static fatigue.[1]

Several approaches have been taken in an attempt to eliminate or reduce static fatigue. One method was to hermetically coat the fiber with either metals or ceramics. Although significant improvements in fatigue resistance were reported, the initial fiber strength and the optical properties of the coated fibers were degraded.[2 3]

Another promising technique involves cladding the fiber with a compressive layer of glass.[4] This surface compressive layer would improve the fatigue resistance of the fiber as well as increase its overall strength.[5]

The objective of the high strength, long length, optical fiber contract was to improve the durability of a long length optical fiber by increasing the surface compression of that fiber. The surface compression will be increased by modifying the interior structure and composition of optical fibers. All fiber layers (with the exception of the thin surface layer) will have relatively low glass transition temperatures and high coefficient of thermal expansion. The surface layer will be fabricated from glass having a higher glass transition temperature and lower thermal expansion characteristics. The resulting surface compression of the fiber should be on the order of 0.69 GPa (100 kpsi). In an effort to achieve these goals, the project was divided into the following tasks:

a. Task 1 - To develop a computer model for the three- and four-layer structure fibers and to optimize the variables for maximum surface compression

b. Task 2 - To develop a fabrication technique for producing high surface compression fibers

c. Task 3 - To evaluate mechanical and optical characteristics of fibers having high surface compression

d. Task 4 - To deliver the high surface compression preform and fiber samples to Naval Ocean Systems Center (NOSC)

2.0 SUMMARY OF WORK ACCOMPLISHED

2.1 Theoretical Computer Models

Theoretical models were developed on a computer for both three- and four-layer optical fibers. This mathematical model was based on the axisymmetric stress/strain equations for cylindrical multi-layer viscoelastic materials.[6]

It is well known that the critical structural parameter in fabricating a durable fiber is the thickness of the compressive surface layer. However, the effects which the material properties of the glasses in the inner layer have on the final surface compressive layer are less obvious. This is due mainly to the interdependency of the various thermal properties within each layer. The theoretical model developed was a preliminary attempt at trying to establish and predict the various stress relationships occurring within a fiber. The models resulted in 8 simultaneous equations for the three-layer fiber and 11 equations for the four-layer fiber. (See Appendix A for Theoretical Stress Analysis and Appendix B for Computer Model Programs.)

The boundary conditions for the mathematical models were based on the actual thermal properties of the glass deposited in the different layers. The thermal properties were measured at Harrop Laboratories from specially prepared specimens. The measured thermal properties are displayed in Table 2-1. To check the

Table 2-1. Thermal Properties Used in Theoretical Stress Analyses.

Fiber Structure	Type		Core	Cladding I	Cladding II	Surface Layer
Three Layer	I	Glass System	$GeO_2 - SiO_2$	$B_2O_3 - SiO_2$	---	SiO_2
		α (10^{-6} in/in/°C)	2.31	1.04		0.66
		T_g (°C)	865	725		1120
	II	Glass System	$GeO_2 - SiO_2$	$B_2O_3 - SiO_2$	---	$TiO_2 - SiO_2$*
		α (10^{-6} in/in/°C)	2.31	1.04		0.05
		T_g (°C)	865	725		1130
Four Layer	I	Glass System	$GeO_2 - SiO_2$	$B_2O_3 - SiO_2$	Vycor	SiO_2
		α (10^{-6} in/in/°C)	2.31	1.04	0.78	0.66
		T_g (°C)	865	725	910	1120
	II	Glass System	$GeO_2 - SiO_2$	$B_2O_3 - SiO_2$	$GeO_2 - SiO_2$*	SiO_2
		α (10^{-6} in/in/°C)	2.31	1.50	2.50	0.66
		T_g (°C)	865	700	870	1120

* Calculated from literature based on the dopant concentration.

accuracy of the theoretical model, data from the ongoing mechanical evaluation were compared to the theoretical values. Tables 2-2 and 2-3 illustrate how the theoretical model compares with measured data. In the case of the three-layer fibers, the two values generally compare quite favorably. However, it should be noted that the theoretical values are generally less than that of the values obtained from the measured static fatigue tests. This small difference was attributed to the fact that the values obtained from static fatigue tests also account for draw induced stresses as well as surface compressive stresses. The theoretically predicted stresses on four-layer structure fibers are considerably lower than the measured values. This was believed due to the slight difference between the thermal properties of the two outer layers.

2.2 Fabrication of Durable Fibers

As mentioned in the previous section, the surface compression of fibers can be increased by decreasing the surface layer thickness. The first approach used in this project was to reduce the thickness of the silica outer layer of the present low loss optical fiber. This was achieved by employing one or more of the following substrate removal techniques: center grinding, flame milling and/or chemical etching. During the course of this contract, these removal techniques were extensively investigated to

Table 2-2. Stress Computation Data of Durable Fibers (Three Layer).

Preform No	Treatment	Dopant/Layer Radius (μm)			Computed Stress (GPa)			Remarks
		1st	2nd	3rd	Theory	SF Test	Bending	
ES 20742A	CE + OD	Ge/54.5	B/59.5	Si/63.5	0.23	0.22	--	
ES 20742B	GR + OD	Ge/54.5	B/61.0	Si/66.0	0.21	0.12	0.26	Oval shape
ES 20746	GR + OD	Ge/54.5	B/62.5	Si/63.5	--	0.21	--	Noncircular core
ES 20749	GR + OD	Ge/49.0	B/57.0	Si/62.0	0.14	0.40	--	Irregular shape
ES 20756A	GR + FP + OD	Ge/53.5	B/59.3	Si/62.3	0.17	0.29	0.38	
ES 20756B	GR + OD	Ge/53.5	B/59.3	Si/62.3	--	0.33	--	
ES 20776	GR + OD	Ge/53.5	B/62.0	Si/65.0	--	0.25	--	Distorted core
ES 20787E	CE + OD	Ge/50.5	B/58.0	Si/61.0	0.17	--	--	Very weak fiber
ES 20833	CE + OD	Ge/41.0	B/55.0	Ti/63.5	0.11	--	--	Very weak core
ES 20844	GR + OD	--	--	--	--	0.25	--	
ES 20871	GR	Ge/31.5	B/61.4	Si/61.4	0.13	0.19	--	
ES 20914	CE + OD	Ge/ --	C/ --	Ti/ --	--	0.15	--	
ES 40226	CE	PGe/57.0	B/63.0	Si/64.5	0.21	0.21	--	

Legend: CE = Chemical Etching GR = Center Grinding FP = Fire Polishing OD = Outside Deposition

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Table 2-2. Stress Computation Data of Durable Fiber (Three Layer) (continued).

Preform No	Treatment	Dopant/Layer Radius (μm)			Computed Stress (GPa)			Remarks
		1st	2nd	3rd	Theory	SF Test	Bending	
ES 40240	CE + OD	Ge/ --	PB/62.5	Si/63.5	--	0.33	--	
ES 40243	CE + OD	Ge/47.0	B/56.0	SI/63.5	0.13	0.13	--	
ES 40251	CE + OD	PGe/45.0	PB/54.0	Si/61.0	0.13	0.33	--	
ES 40301E	CE	Ge/ --	B/ --	Si/61.2	--	0.49	0.33	Nonuniform core
ES 40332A	GR + FP + OD	Ge/55.5	B/63.5	Si/64.5	0.22	0.31	--	
ES 40363	GR + OD	Ge/48.5	B/57.0	Si/66.0	0.12	0.17	--	
ES 40371E	CE + OD	Ge/50.0	B/58.1	Si/61.6	0.23	0.23	--	
ES 40371G	GR + OD	Ge/45.0	B/58.5	Si/61.6	0.15	--	--	
ES 40383	GR + OD	Ge/44.0	B/57.0	Si/63.5	0.15	--	--	
ES 40418	GR + FP + OD	Ge/25.5	B/60.5	Si/63.5	0.12	0.17	--	
ES 40427	GR + OD	Ge/27.5	B/62.5	Si/63.5	0.15	0.13	--	
ES 40460	GR + OD	Ge/27.0	B/59.5	Si/63.5	0.12	0.23	--	High B dopant core
ES 40489H	CE	Ge/27.5	B/60/0	Ti/63.5	0.31	0.67	0.67	
ES 40489I	CE	Ge/27.5	B/57.5	Ti/63.5	0.26	0.59	0.74	
ES 40498I	CE	Ge/23.5	B/57.5	Ti/63.5	0.26	0.33	0.35	

Legend: CE = Chemical Etching GR = Center Grinding FP = Fire Polishing OD = Outside Deposition

Table 2-2. Stress Computation Data of Durable Fibers (Three Layer) (continued).

Preform No	Treatment	Dopant/Layer Radius (μm)			Computed Stress (GPa)			Remarks
		1st	2nd	3rd	Theory	SF Test	Bending	
ES 40500II	CE	PGe/--	PB/--	Ti/--	--	0.12	--	
ES 40518	CE + OD	Ge/--	PB/--	Ti/--	--	--	--	
ES 40584	CE + OD	PGe/--	PBGe/--	Ti/--	--	--	0.06	
ES 40656A	CE	PGe/--	PB/--	Ti/--	--	--	0.66	

Legend: CE = Chemical Etching GR = Center Grinding FP = Fire Polishing OD = Outside Deposition

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Table 2-3. Stress Computation Data of Durable Fibers (Four Layer).

Preform No	Treatment	Composition and Dimensions				Computed Stress (GPa)			Remarks
		1st	2nd	3rd	4th	Theory	SF Test	Bending	
ES 40298	OD	Ge/--	B/--	Vy/62.5	Si/63.5	0.06	0.46	0.38	Distorted core
ES 20763	OD	Ge/25.5	B/29.5	Vy/60.5	Si/63.5	0.05	0.21	--	
ES 20781	OD	Ge/13.0	B/19.5	Vy/57.5	Si/62.5	0.04	0.33	0.26	
ES 40487	CE	Ge/14.0	B/23.5	Ge/43.7	Si(Ti)/63.5	0.14	0.18	--	High Ge-dopant *
ES 40496	CE	Ge/21.7	B/26.0	Ge/--	Si(Ti)/63.5	--	0.18	--	High Ge-dopant **
ES 40492A	CE	Ge/16.5	B/22.0	Ge/55.0	Si(Ti)/63.5	--	0.74	0.63	High Ge-dopant

* High Ge-dopant cladding thin Ti-doped layer

** High Ge-dopant cladding dark Ti-doped ring

Legend: CE = Chemical Etching GR = Center Grinding FP - Fire polishing OD = Outside Deposition
Vy = Vycor ®

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characterize their process parameters. The partial removal of substrate material, using these techniques, produced three-layer structure fibers.

The second approach used in the fabrication of compressive layers was the outside deposition of low thermal expansion glasses such as pure silica and Ti-doped silica.[7] This was performed on collapsed preforms where the substrate material was either all or partially removed. Using this approach, either three- or four-layer structured fibers could be fabricated. Figure 2-1 illustrates how the first two approaches were used to fabricate durable fibers. The surface compressive layer thickness of the actual fibers varies from 0.5 μm to 9 μm.

Since both the outside deposition and some of the substrate removal techniques showed a tendency toward degradation of both initial and fatigue strength, a third approach was investigated. This approach required the internal deposition of a Ti-doped silica layer. This deposition was performed before the sequential deposition of optical cladding and core glasses in the substrate tube. The final fiber was drawn from the preform whose substrate material was completely removed by chemical etching. This etching would expose the previously deposited thin Ti-doped silica layer.

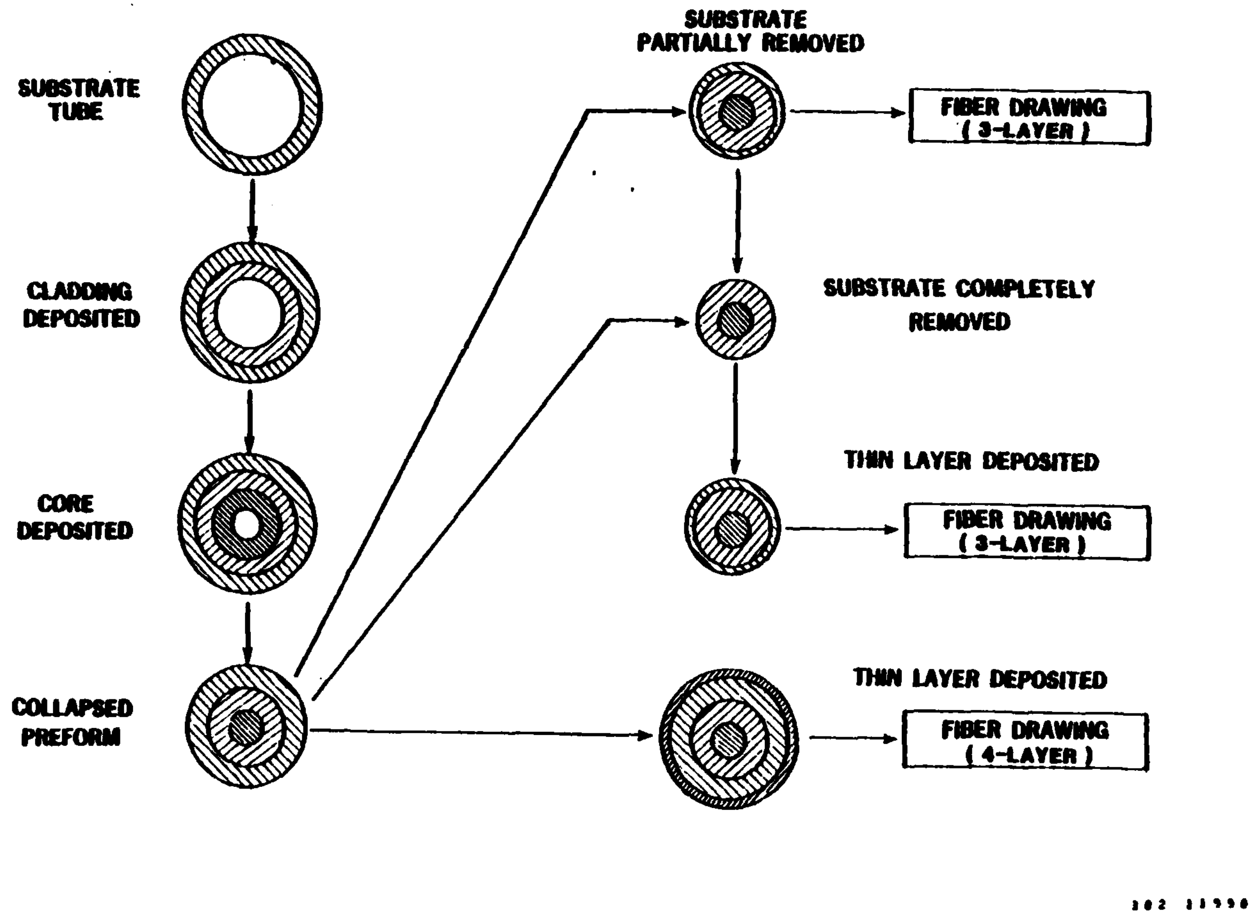

Figure 2-1. Initial Approaches of Durable Fiber Fabrication.

This approach is shown in Figure 2-2. Figure 2-3 shows the typical microphotographs of Ti-doped silica layer fiber cross section. The bright outer ring in the microscopic end photo of the fiber is the Ti-doped silica layer. This particular fiber showed a high fatigue resistance. A high surface compression of 0.641-0.744 GPa (93-108 kpsi) was deduced from the static fatigue tests.

In addition to the Ti-doped silica outer layer, the concentration of higher thermal expansion materials (such as P-doped borosilicate glass and high Ge-dopant glass) were increased in the inner layers. As a result the highest fatigue resistance was observed in the static fatigue test of higher dopant glass fiber (i.e., ES 40492).

A total of 186 preform starts was begun under this program. Of these starts, 164 were step index preforms, 16 were graded index preforms, and 6 were simple silica rod-type preforms. Of the 164 step index preforms, 57 were fabricated with an internal compressive layer. Once the preform was fabricated, the total preform, or section of the preform, was treated. Of the preforms fabricated, 31 preforms were center ground, 3 were flame milled, 72 were chemically etched, and 48 underwent outside deposition.

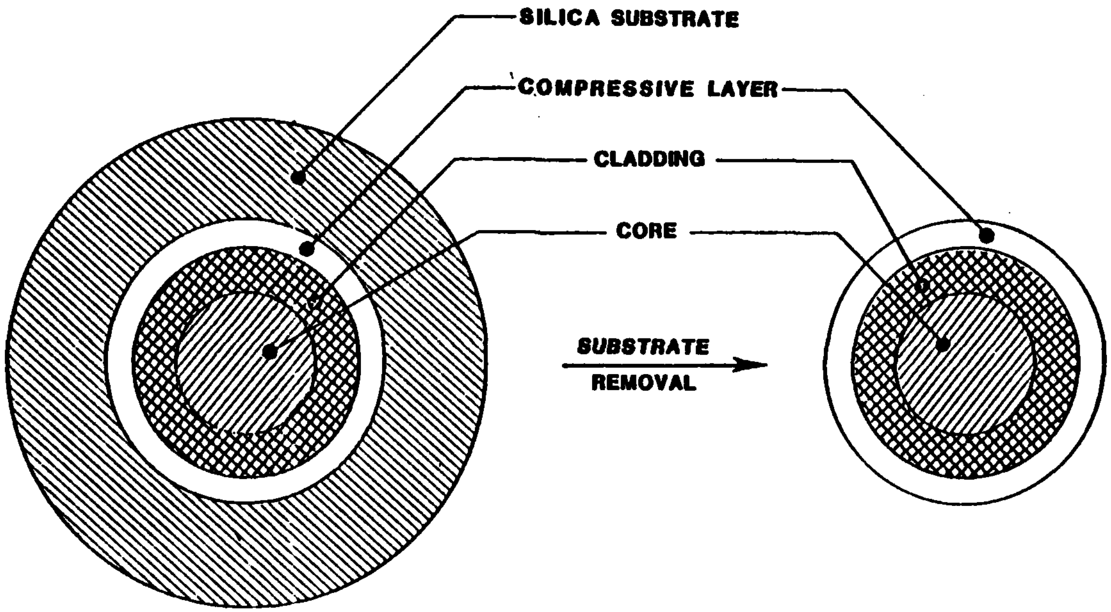

Figure 2-2. Durable Preform Fabrication of Internally Deposited Compressive Layer.

Figure 2-3. End Photo of Durable Fiber Drawn From Preform ES 040489B.

A total of 93 fibers was drawn from preforms or parts of preforms. Of these drawn fibers, 95 fibers were mechanically evaluated. The total number of preforms/fibers fabricated for this program is listed in Appendix C. Details of the fabrication processes are described in the Process Specification, Item A006, of this contract (see Appendix E).

2.3 Evaluation of Surface Compression Fibers

Since the major thrust of this program was to increase the durability of fiber through the use of a compressive cladding, the fibers were evaluated mechanically in several different ways. First, static fatigue tests were performed on the fiber at ambient atmosphere using the classical mandrel technique. The static fatigue resistance parameter, N, was determined from the slope of log-log plot of breaking stress versus the time-to-failure as displayed in Figure 2-4. To determine the surface compression, the fibers were compared to plastic clad silica (PCS) fibers which have no surface compression.

Dynamic tensile strength of 2 m gage length fibers was evaluated using 23% strain rate and the strength distribution was presented as a Weibull plot. Further evaluation such as dynamic fatigue tests on selected fibers was performed.

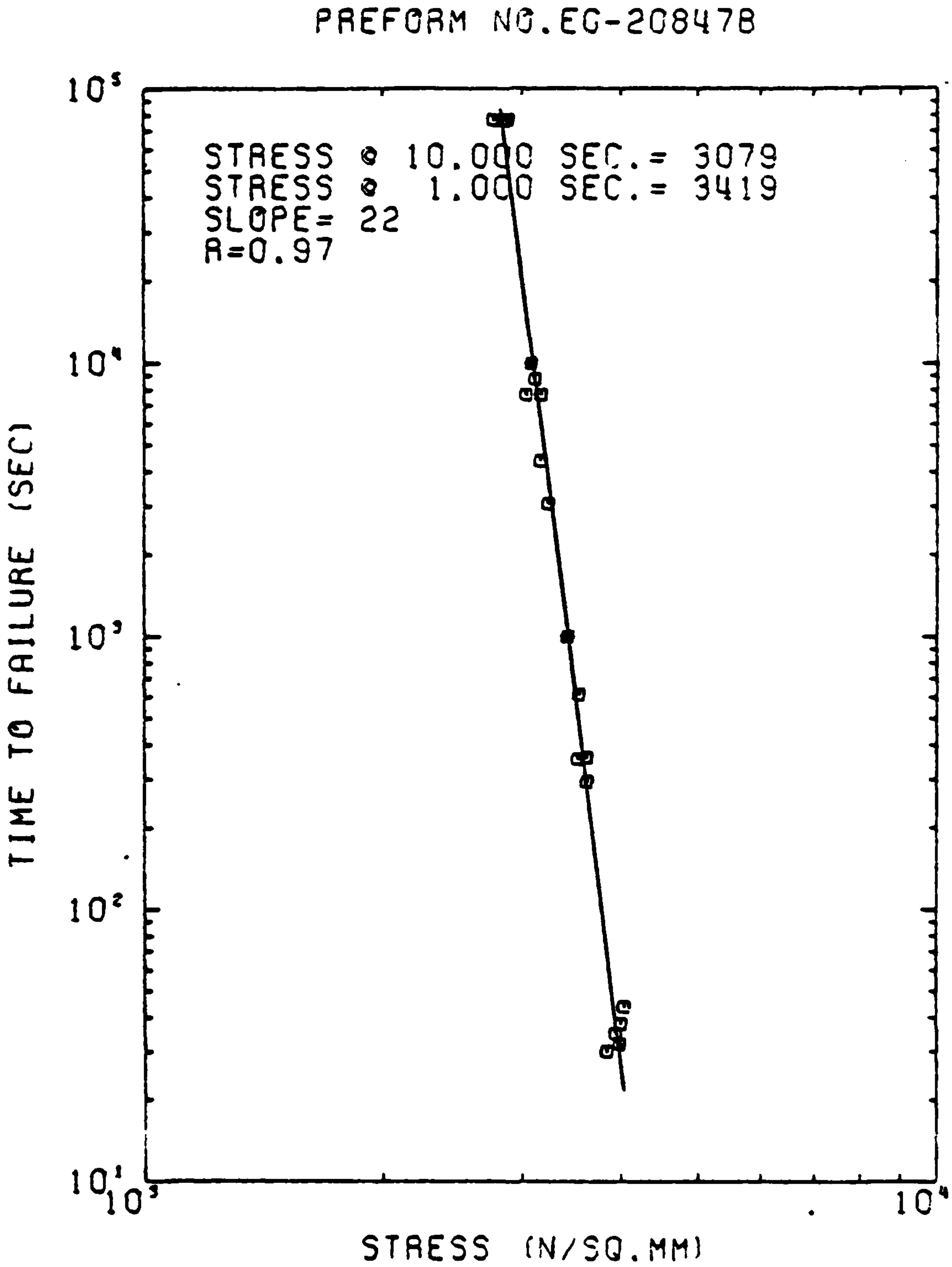

Figure 2-4. Static Fatigue of Typical Durable Fiber.

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Improvement in the durability of surface compression fibers was determined quantitatively by comparing the N values and the breaking stresses at the specified time-to-failure to the data obtained from PCS fibers. Fibers having a thin surface compressive layer generally showed higher N values and breaking stress values. An increase in both the N and breaking stress values was considered to be the result of the compressive stress developed on the fiber. The breaking stress level increases were compared to the theoretically predicted stresses and showed close agreements in most of the three-layer structure fibers. To supplement the compressive stress level measurements a photoelastic technique was used to determine the surface compressive stress.[4] This technique proved not to be suitable for measuring stress in a very thin compressive layer due to its limited resolution.[8] Abraded strength tests were also performed on the available compression fibers to evaluate the technique as an alternative testing method.[9] These test results were not promising again due to very thin surface compressive layers.

Finally, a pure bending stress test was found to be a simple and reliable technique to indirectly measure the compressive stress level on the fibers. A comparison between the surface compression values determined using static fatigue test and the values measured by bending test are shown in Table 2-4; one of the typical results is shown in Figure 2-5.

Table 2-4. Comparison of Surface Compression Computed by Different Techniques.

Preform No	Fiber Structure	Stress (GPa) Static Fatigue Test	Stress (GPa) Bending Test	Remarks
ES 20742B	Three Layer	0.12	0.26	Silica outer layer
ES 20756A	Three Layer	0.29	0.38	Silica outer layer
ES 40301E	Three Layer	0.49	0.33	Silica outer layer
ES 40489B	Three Layer	0.67	0.67	Ti-doped outer layer
ES 404891	Three Layer	0.59	0.74	Ti-doped outer layer
ES 40498I	Three Layer	0.33	0.35	Ti-doped outer layer
ES 20781	Four Layer	0.33	0.26	Vycor ® sub-strate
ES 40298	Four Layer	0.46	0.38	Vycor ® sub-strate
ES 40492	Four Layer	0.74	0.63	High Ge-dopant cladding

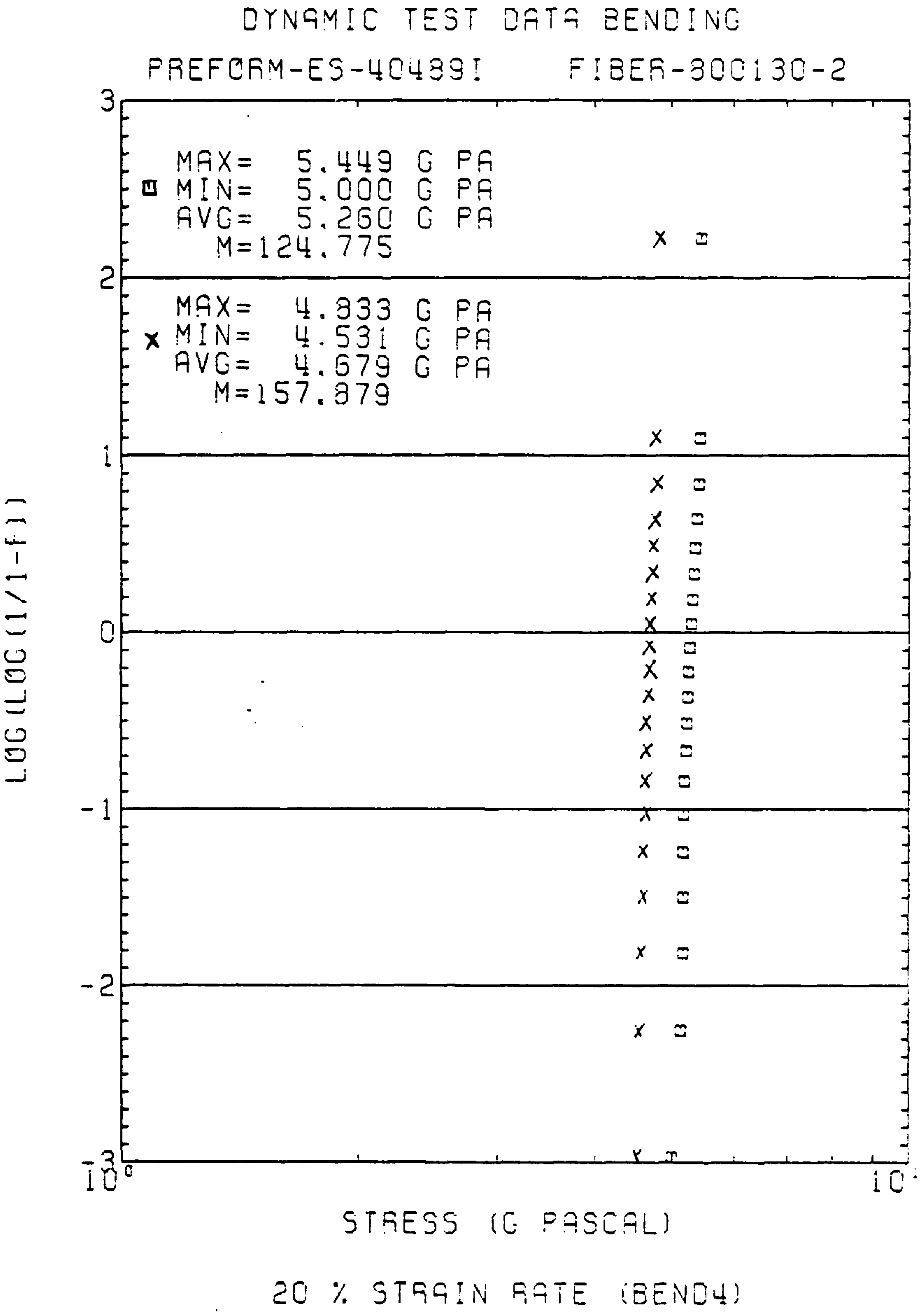

Figure 2-5. Bending Test Results Compared With Plastic Clad Silica Fibers.

The raw data from mechanical evaluation test were entered into a computer. The data were refined and the results printed and plotted. An example of this program is displayed in Appendix D.

3.0 SUMMARY OF FINDINGS

3.1 Theoretical Computer Model

As described previously, the main concept employed to produce compressive cladding depended upon the development of thermally induced stresses within the fiber. These stresses were basically dependent on the mismatch of the thermal properties (thermal expansion coefficient and glass transition temperature) of the various glasses used in the fabrication of the fiber. The theoretical approach used in this program was essentially the same as that used by Krohn and Cooper in their two-layer fiber study.[4] Similar assumptions and boundary conditions were also used in the three- and four-layer theoretical models.

It should be noted that the stresses induced by other mechanisms such as quenching stress, frozen-in stress, and mechanically induced stress were excluded from the analysis.[8] These stresses are generally considered to be insignificant in fibers drawn under typical drawing conditions.

Since the induced axial stress distribution in multilayer structures must be balanced, the compressive surface layer thickness is the critical structural parameter in fabricating a durable fiber. To maximize the surface compression, the layer thickness should be minimized. The surface layer thickness of most fibers was more than 1 μm. This was determined from microscopic observation of cross sections of the drawn fibers. However, it should be noted that nonuniform layer thickness was often observed in the compressive layer of the fiber. The nonuniformity was attributed to variation in the substrate tube's wall thickness and unstable collapse conditions.

In addition to the structural parameters, the material properties of the glasses in the fiber were also very important in determining the amount of compression developed in the outer layer. The two most important material parameters in development of a compressive layer were the transition temperature and the thermal expansion coefficient of the various glasses. Through the use of the theoretical model, it was determined that the thermal expansion coefficient was the most influential material parameter. Using hypothetical calculations, surface compressions of up to 0.69 GPa (100 kpsi) could easily be achieved in the compressive layer by varying the appropriate thermal expansion coefficients. The results of these theoretical calculations are displayed in Figure 3-1. However, attempts to fabricate preforms based on theoretical calculations showed a high incidence of failure during the preform fabrication processes. These failures were attributed to the high tensile stresses in the innermost layer. In an effort to reduce the magnitude of the tensile stress in the innermost layer, the composition of the core and cladding glasses was further modified in such a way as to minimize the difference in

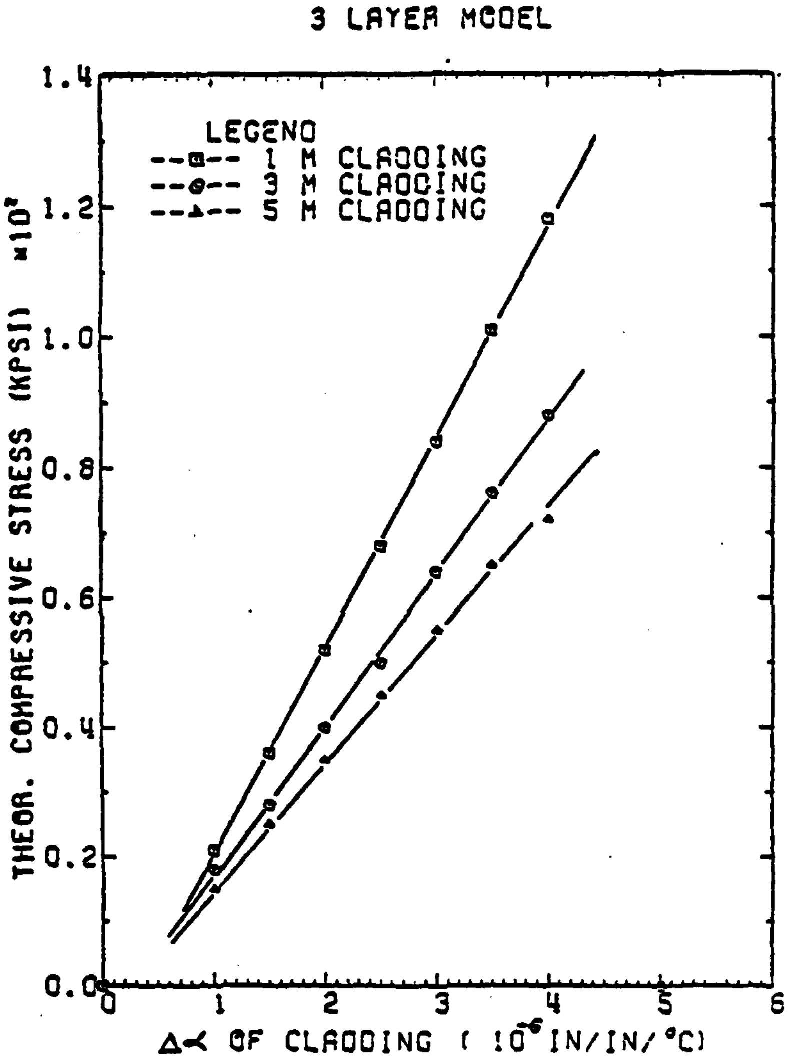

Figure 3-1. Effect of Differential Thermal Coefficient on Compressive Stress.

the thermal expansion coefficients. This, along with structural changes based on theoretical analysis, resulted in the fabrication of durable fibers with a compressive layer of 0.69 GPa (100 kpsi).

The thermal property data of optical glass systems used in the theoretical analysis are shown in Table 2-1. However, the actual thermal properties of the glass systems could be different from the measured values due to the high cooling rates present during the fiber forming process.[10 11]

3.1.1 Three-Layer Structure Fiber

Basically two types of three-layer fibers were fabricated. The two types were similiar in most respects except that type I had a plain silica compressive layer and type II had a titanium doped silica compressive layer (see Table 3-1 for typical compositions).

Surface compressive stresses up to 0.24 GPa (35 kpsi) were predicted from the theoretical models of type I three-layer fibers. As shown in Table 3-1, the theoretical stresses of most fibers were in close agreement with the stresses determined experimentally from the static fatigue tests. However, these stress levels have not been directly verified due to the lack of a suitable method of stress measurement. (This subject will be discussed in more detail in the section on evaluation of compressive stress fibers.)

Table 3-1. Surface Compressive Stresses on Durable Fibers.

Preform No	Fiber Structure	Type	Stress (GPa) Theoretical Prediction	Stress (GPa) Static Fatigue Test	Remarks
ES 20742A	Three Layer	I	0.23	0.22	
ES 20742B	Three Layer	I	0.21	0.12	Oval shape
ES 20749	Three Layer	I	0.14	0.40	Irregular shape
ES 20756A	Three Layer	I	0.17	0.29	
ES 20871	Three Layer	I	0.13	0.19	
ES 40226	Three Layer	I	0.21	0.21	
ES 40243	Three Layer	I	0.13	0.13	
ES 40251	Three Layer	I	0.13	0.33	
ES 40332	Three Layer	I	0.22	0.31	
ES 40363	Three Layer	I	0.12	0.17	
ES 40371E	Three Layer	I	0.24	0.23	
ES 40418	Three Layer	I	0.12	0.17	
ES 40460	Three Layer	I	0.12	0.23	

Table 3-1. Surface Compressive Stresses on Durable Fibers (continued).

Preform No	Fiber Structure	Type	Stress (GPa) Theoretical Prediction	Stress (GPa) Static Fatigue Test	Remarks
ES 40489B	Three Layer	II	0.31	0.67	
ES 40489I	Three Layer	II	0.26	0.59	
ES 40498I	Three Layer	II	0.26	0.33	
ES 20763	Four Layer	I	0.05	0.21	
ES 20781	Four Layer	I	0.04	0.33	
ES 40298	Four Layer	I	0.06	0.46	Distorted core
ES 40487	Four Layer	II	0.14	0.18	
ES 40492	Four Layer	II	0.20	0.74	
ES 40496	Four Layer	II	0.17	0.18	

Three-layer type II fibers having a Ti-doped silica surface layer displayed higher theoretical and measured compressive layers than the type I. This higher stress level is generally attributed to the lower thermal expansion coefficient of the Ti-doped silica. Theoretical stresses up to 0.31 GPa (45 kpsi) were predicted for the type II fiber. Table 3-1 shows that in every case the theoretical values were less than the actual measured values. This difference was attributed to an inability to properly measure the thermal properties of the Ti-doped silica. The thermal properties of Ti-doped silica are strongly dependent on the fabrication processes. The fabrication processes present in fiber drawing could not be duplicated in the bulk samples required for thermal property measurements.

3.1.2 Four-Layer Structure Fiber

Type I of four-layer fibers having an extra silica layer formed by outside deposition on the untreated Vycor® substrate is listed in Table 2-3. Stresses computed from four-layer fiber models are considerably lower than the theoretical stresses of three-layer models. Furthermore, the theoretically predicted stresses are also less than those of the values obtained by static fatigue tests. The possible sources of this discrepancy will be discussed in the section on evaluation of the compressive stress.

Four-layer, type II fibers have an extra thick silica layer which was not completely removed over an internally deposited thin Ti-doped silica layer (75 µm). Type II fibers also have an extra high thermal expansion cladding layer with high Ge-dopant in order to increase the surface compression. Therefore, the type II fiber is actually a five-layer structure fiber, but the Ti-doped layer is very thin compared to the outer silica layer. The theoretical stresses computed from a four-layer model could be inaccurate due to a possible contribution of a Ti-doped layer.

3.2 Fabrication of Durable Fibers

3.2.1 Preform Fabrication

All preforms were fabricated by the modified chemical vapor deposition (MCVD) technique. The optical borosilicate cladding and highly doped germanosilicate core were deposited sequentially either in a pure silica or a high silica substrate tube by the internal vapor phase oxidation process. After collapsing the preform, the substrate material was either completely or partially removed in order to form a thin surface compressive layer resulting in a three-layer structure fiber. In the case of four-layer structure fiber fabrication, the extra silica layer as a compressive stress layer was externally deposited on the Vycor® substrate preform. The details of the preform fabrication processes are described in the process specification report and the findings of the specific process will be discussed in the following paragraphs.

3.2.1.1 Internal Deposition

The chlorides of germanium, silica, phosphorous, boron, and titanium are quantitatively dispensed into the glass substrate tube where they are oxidized and form glass layers. The designed geometry is achieved after the substrate is collapsed into a preform. Various commercial substrate tubes such as WG®-2, TO®-8, SS®-2, and Vycor® were used for the fabrication of durable fibers.

The process of internal deposition of these optical oxide glasses has been well established because these materials except Ti-doped silica are customarily used for optical waveguides. However, the properties of each layer had to be modified by varying the amount and type of dopant in order to increase the surface compression in the durable fibers.

Basically, optical cladding is formed by the addition of boron as B_2O_3, which reduces refractive index (RI), lowers T_g, and increases α, while the optical core is formed by adding GeO_2 and/or P_2O_5 which increase RI, lower T_g, and increase α.[12] The practical fabrication limit to the amount of dopant should be set by allowable maximum thermal mismatch between the substrate and deposited glasses. For example, if the mismatch is too great, the internal stress will cause the preform to shatter either during or immediately after preform collapsing. This problem was controlled to some degree by use of a ribbon burner and by changing inner layer glass composition to modify the stress profile. Furthermore, preform dimension controls such as circularity and uniformity were quite difficult to maintain if either deposited glass or substrate glass (such as Pyrex® glass) is extremely soft or has a lower Tg compared to the silica glass.

3.2.2 Substrate Removal

Several techniques have been employed to obtain the desired structural layer thickness in the preforms for this program. These techniques are described in the following paragraphs.

3.2.2.1 Center Grinding

This method consisted of mechanical grinding of the substrate layer for either partial or complete removal. During the early stages of this program, mechanical grinding was an attractive method for substrate removal. Extensive preliminary work was done on short preforms to establish optimum operating procedures. The centering of the preform in the grinding lathe and the circularity of the substrate tube were the critical parameters controlling uniform substrate removal.

The amount of glass to be removed from the collapsed preform is determined by measurements made on an end photograph of a cane drawn from the initial preform. Careful measurements of the cane photolayer ratios and of the actual preform outer diameter (od) allow calculations of the depth to which the preform must be ground. After completion of the grinding, the remaining preform was rinsed in diluted hydrofluoric acid and fire polished to give a smooth surface prior to any subsequent operation.

In the case of partial substrate removal, the preform is drawn into a fiber. In the case of complete removal, an outer layer of a selected composition is outside vapor deposited over the exposed cladding layer before the preform is drawn into fiber. (Outside deposition will be discussed in a later section.)

Thirty-one preforms were fabricated using the grinding technique, and various glass compositions were outside deposited. In all cases, no appreciable increase in surface compression was observed in drawn fibers. In many cases, the dynamic strength test showed a multimodal failure distribution in these fibers. A multimodal dynamic strength distribution indicates that the static fatigue analysis is unreliable.

It was felt that the grinding process introduced flaws and impurities into the preform surface which were subsequently transferred to the fiber as it was drawn. In order to investigate this, some graded index preforms and some solid synthetic silica rods were cut into several sections each, and each section was given different treatment prior to fiber drawing. The results are shown in Table 3-2.

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Table 3-2. Effect of Processing on Strength.

Preform No	Treatment(s) Received	M	Dynamic Strength Test Data			Static Fatigue Test Data			Preform Type
			Max (GPa)	Min (GPa)	Mean (GPa)	N	Stress @ 10^3 s (GPa)	Stress @ 10^{11} s (GPa)	
ES 40395	None	59	5.56	2.39	4.90	20	2.89	2.58	SS®-2 Rod
ES 40409	G+FP	55	5.52	4.63	5.19	20	3.25	2.89	SS®-2 Rod
ES 40410	G+OD	Multi-mode	5.60	3.46	5.20	18	3.26	2.87	SS®-2 Rod
ES 40428A	None	67	5.04	4.39	4.79	19	3.05	2.71	SS®-2 Rod
ES 40428B	G+FP+OD(S)	Multi-mode	5.81	4.85	5.44	20	3.31	2.96	SS®-2 Rod
EG 20774	None	40	5.81	4.36	5.31	27	3.63	-	Graded Index
EG 20774A	G+OD	9	2.08	0.72	1.24	22	3.32	2.98	Graded Index
EG 20774B	G+FP	60	5.61	4.72	5.20	24	3.59	-	Graded Index

Legend:

G = Ground
FP = Flame polished
OD = Outside deposited
S = SiO_2
E = Etched

In general, the treated silica rods when compared to the untreated silica rods produced fibers with as good or better strength and fatigue characteristics. However, when the treated preform is compared to the untreated preform, a degradation in the dynamic and fatigue properties was observed. In the latter case, the preforms that showed degradation were treated by grinding. On the basis of this data, grinding of preforms to remove the substrate layer was not chosen to be the final technique for the durable fiber preform treatment.

3.2.2.2 Flame Milling

The flame milling approach relies on a high temperature heat source such as a CO_2 laser or H_2/O_2 torches to vaporize the substrate material. In this project flame milling was accomplished by employing a slowly traversing H_2/O_2 torch flame to heat the outer surface of the preform. Preform ES 40287 was treated in this fashion. This preform was fabricated using a substrate tube of Vycor® glass. Vycor® contains a slight quantity of sodium, and the sodium gives the oxyhydrogen torch flame a distinctive yellow color. The absence of sodium yellow in the torch flames was used as an indicator of complete substrate removal for the flame milling experiment.

The high silica substrate material has a much higher melting temperature than the materials used for core and cladding. Because of the high temperature required for flame milling Vycor®, the preform warped during milling. This warpage effect steadily increased as the preform diameter decreased during each milling pass of the torches. The warpage causes the preform to axially run out of the milling flame. This run out, in turn, results in incomplete and/or nonuniform removal of the substrate glass. After several experiments, flame milling was abandoned as an alternative removal technique. However, this warpage problem can be either reduced or eliminated by using a preform produced with a thick Vycor® substrate tube (e.g., 25-mm precision Vycor® tubing).

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3.2.2.3 Chemical Etching

The technique of etching was evaluated as a potential method of fabricating a surface compressive layer on preforms. Preforms were etched with hydrofluoric acid to form the surface compressive layer by either of two procedures:

a. A complete substrate removal was followed by an outside deposition of a thin layer; the deposited layer subsequently formed compressive cladding on the drawn fiber.

b. A complete substrate removal exposed a previously deposited thin layer inside the preform. The exposed layer subsequently formed compressive cladding on the drawn fiber.

Four types of substrates, Vycor®, TO®-8, WG®-2, and SS®-2 were evaluated in order to compare their etching properties. Preliminary evaluations showed that Vycor® etched faster than the other substrates. However, during the preform fabrication process, the use of Vycor® as the substrate resulted in several bubbles at the substrate/cladding interface and also in the substrate itself. Preforms having bubbles, inclusions, or other types of localized inhomogeneity are not suitable for the etching process. These localized inhomogeneities will sufficiently change the rate of etching. The changing etching rate will result in pits or bumps along the length of the preform. Further testing showed that TO®-8 substrates did not etch uniformly along the length of the preform because of these compositional nonuniformities. The WG® substrates, although yielding preforms without pits, have an etching rate which is relatively slow when compared to Vycor®. Preforms fabricated with SS®-2 substrates generally did not have any pits and etched very uniformly along the length of the preforms. Two preforms having SS®-2 substrates were etched successfully to the substrate/cladding interface without any pit formation or damage to the preform. It should be pointed out that substrates used for preform fabrication do not form an integral part of the final preform having compressive cladding. Therefore, it was desirable to use an inexpensive substrate which can also etch uniformly. Unfortunately, the SS®-2 substrate tubes (when compared to other substrates) were prohibitively expensive.

Aside from some of the problems with the etching technique, the technique was judged to be the most effective technique used in this program. Most of the final deliverables for this program were fabricated using WG® substrate tubes followed by the etching substrate removal technique. There are still some fundamental problems with the chemical etching technique. At present, there is no control to assure uniformity prior to fabrication in the etched layer nor to prevent formation of pits. Possible solutions were investigated. One solution called for the deposition of a barrier layer, which would prevent or retard the acid from etching beyond a predetermined depth. Another possible solution required the use of buffered acids as etchants; this acid would selectively etch glass of a given composition. The data indicated the need for a more extensive study of this technique in order to establish optimum etching conditions. A more complete investigation was beyond the scope of this project.

During the course of this program the shattering of preforms became a problem. It is believed that occasional material defects and nonuniform layer thickness, caused by localized temperature distribution during preform collapsing, resulted in the formation of residual stress concentrators in the preform.[13] These stress concentrators were potential sources of preform shattering during etching. When detected through the use of polarized light they are eliminated.

Another possible source of shattering could be the joint between the preform and the TO®-8 holders. These joint sections, as well as the ends of the preforms, are covered with paraffin wax in order to block the possible effects of hydrofluoric etchant in these areas. As a result, the incidence of shattering problems during the chemical etching process has been considerably reduced.

3.2.3 Outside Deposition

Outside deposition was achieved by attaching a hydrogen oxygen deposition torch to the moving carriage of a standard CVD lathe. While the collapsed preform rotated, the deposition torch would traverse the length of the preform depositing a glass material.

By connecting the torch to standard CVD bubblers, it was possible to deposit both pure silica and titanium doped silica. In order to determine the effect of outside deposition on the resulting fibers, a series of experiments was performed. In this experiment, 10-mm SS®-2 rods were cut into four or five parts and drawn into fibers after one of the following treatments:

a. Drawn as received

b. Outside deposit only (SiO_2)

c. Ground plus outside deposit (SiO_2)

d. Etched plus outside deposit (SiO_2)

e. Etched plus outside deposit ($TiO_2 \cdot SiO_2$)

Table 3-3 displays the results obtained from the experiment. The SS®-2 preform rods with an asterisk following the number are all cut from one rod. The rod numbers which are the same (except for the last letter) were all cut from another SS®-2 rod.

Although scattered, the data indicate that outside deposition of silica (SiO_2) does not seriously degrade the strength of SS®-2 rods. Similar results have been reported by other investigators.[14] When the outside deposited material is Ti-doped silica, as in the case of ES 40428D, there appears to be a definite improvement in the strength and durability of the resulting fiber.

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Table 3-3. Strength/Durability of Untreated and Treated SS®-2 Rods.

		Dynamic Strength Test Data				Static Fatigue Data		
Preform Treatment	SS®-2 Number and Material	Max (GPa)	Min (GPa)	Mean (GPa)	Std Data (GPa)	Stress @ 10^3 s (GPa)	Stress @ 10^4 s (GPa)	N
As received	ES 40395*	5.56	2.39	4.96	0.64	2.88	2.58	20
	ES 40428A	5.04	4.39	4.78	0.16	3.05	2.70	19
Outside deposition only	ES 40394* (Si)	5.58	4.65	5.28	0.23	3.08	2.72	18
	ES 40411* (Si)	5.60	4.51	5.08	0.28	3.26	2.96	24
Ground and flame polish	ES 40409*	5.51	4.62	5.19	0.25	3.25	2.89	20
Ground, flame polish and outside deposition	ES 40410* (Si)	5.60	3.46	5.19	0.47	3.25	2.87	18
	ES 40428B (Si)	5.80	4.85	5.40	0.23	3.31	2.95	34
Etch, flame polish, and outside deposition	ES 40428C (Si)	5.70	4.33	5.21	0.35	3.18	2.83	20
	ES 40428D (TiSi)	5.96	4.65	5.18	0.41	3.43	3.14	25

*Cut from one rod

Throughout the course of the program the outside deposition technique tended to show an increase in the durability of the fiber. However, the data were often very scattered. A possible source of this data scattering may be in the outside deposition process itself. During the deposition it is believed that impurities present in the air were incorporated into the deposition process. These impurities were detected as small bright flashes of light in the torch flame during the outside deposition process. Although some physical techniques were employed in an attempt to reduce the concentration of these solid impurities, the flashes persisted.

3.2.4 Fiber Fabrication

Final preforms having either three-layer or four-layer fiber structure were drawn to maximum fiber length after establishment of the stable draw conditions. Most finished preforms except four-layer type I fiber preforms were short and thin (i.e., <10 in length with 5 to 6 mm outside diameter (od)) because of substrate layer removal. The resulting fiber lengths were less than 500 m; these were not long enough to permit complete evaluation of mechanical and optical performance. The optimum drawing condition of each fiber draw was not easy to establish with these short and thin preforms.

All fibers were drawn using O_2/H_2 flame torches in order to eliminate the possible effect of contamination from the furnace on the fiber strength. The closed loop feedback diameter control was employed to minimize fiber diameter fluctuations. The diameter control of ±2% or ±3% for a 127 μm fiber diameter was achieved for the most fiber draws with occasional higher fluctuation up to ±5%.

The primary silicone RTV (Sylgard® 184) coating was applied by dip-coating immediately below the fiber diameter control sensing head. The secondary coating of copolyester Hytrel® was applied by extrusion on-line before the fiber was taken up on the spool. The final jacket diameter was 20 ±2 mils (500 μm ±50 μm).

3.3 Evaluation of Compressive Stress Fibers

The first concern of this program is the improvement of mechanical performance rather than optical performance as addressed in the objectives of this program. First, all fibers fabricated by the developed techniques were subjected to mechanical evaluation using various evaluation techniques as presented in the original proposal. Then, the selected fibers longer than 500 m were evaluated for their optical performance such as attenuation loss and dispersion using the standard measurement methods. There are a few fibers whose lengths are longer than 500 m after the mechanical evaluation due to the limited volume of the finished preform.

3.3.1 Evaluation Techniques - Mechanical Performance

3.3.1.1 Static Fatigue Test

The results of static fatigue tests performed on the compressive stress fibers are listed in Table 3-1. Table 3-3 also includes the data for plastic clad silica (PCS) fibers as the references. The fatigue resistance parameter, N, varies from 19 to 32, which was determined from the slope. The slope of the static fatigue test curve was determined by a regression analysis of more than 15 data points with a higher correlation coefficient (i.e. >0.95). However, an increase in the spread of fatigue data was occasionally observed due to large flaw size distribution. In this case, the quantitative comparison of N values seemed to be difficult. Furthermore, the possible errors caused by the large uncertainty in low values of time-to-failure (i.e. >10 s) with small mandrel size) were considered. The good reproducibility of a static fatigue test, was confirmed by performing separated tests as shown in Figure 3-2. Generally, the N value is strongly dependent on glass surface composition, testing conditions, crack growth characteristics, and coating materials.[15]

In addition to the increase in N value, the stress level increase of durable fibers when compared to PCS fibers was used as an indicator of the relative fatigue resistance improvement. Therefore, the breaking stress level increase at a specified time-to-failure may not represent the actual value of surface compressive stress

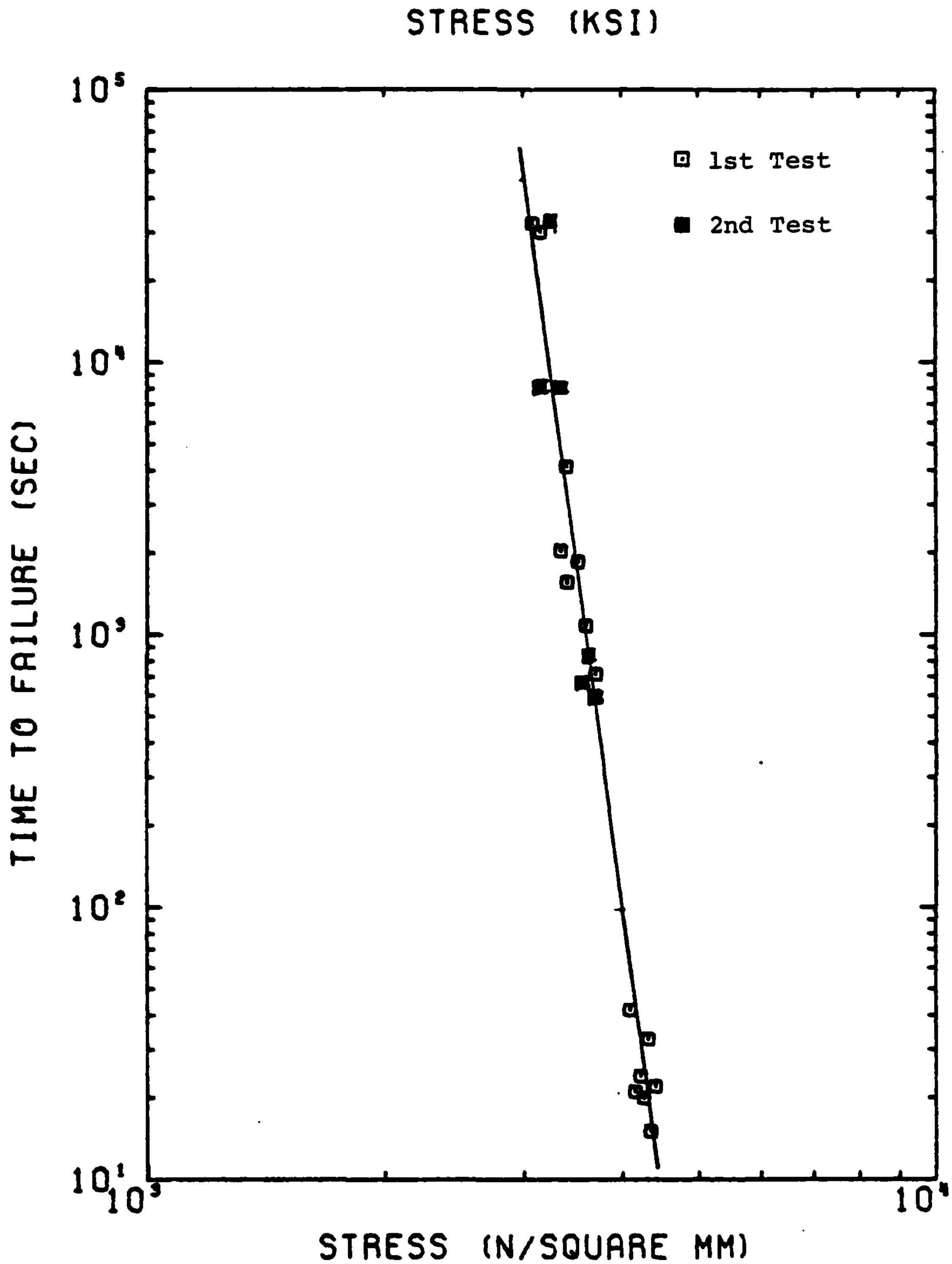

Figure 3-2. Reproducibility of Static Fatigue Test on Durable Fiber (ES 40240).

developed on the fiber even though there is a correlation between the compressive stress and failure time as shown in the following equation:[16 17]

$$\log\left(\frac{t}{t_c}\right) = N \log\left(\frac{\sigma_a - \sigma_c}{\sigma_a}\right) \qquad (3\text{-}1)$$

where t and t_c are the times-to-failure of fibers having no compressive cladding and compressive stress (σ_c) under the same applied stress (σ_a), respectively. The surface compression stress data deduced from the static fatigue data of typical three-and four-layer fibers having a silica surface layer showed relatively good agreement with the theoretically predicted data from the equation 3-1 if unrealistic assumption of a constant N is taken into account.

These experimental data were also compared to the predicted data from the theoretical model. Stresses associated with three-layer fiber models are in close agreement with the stresses determined experimentally from the static fatigue tests of fibers having a silica compressive layer. However, the Ti-doped compressive layer fibers showed that the theoretical data are relatively lower than those determined from the static fatigue data which showed the high durability. Considerable discrepancies were also noticed in the four-layer models, as shown in Table 3-1. These discrepancies could be attributed to several possible sources. The exact values of glass properties especially above T_g are not known and the assumption of material properties such as constant Young's modulus could not be correct in the theoretical model as reported by other investigators.[18] The contribution of mechanically induced stresses should be considered in the high silica substrate preforms. For example, four-layer Vycor® substrate preform prepared by outside deposition without the milling process could give quite different drawing conditions and also resulted in different static fatigue characteristics because of unique surface flaw distributions associated with preform fiber fabrication processes. Possible surface modification by outside deposition of thin silica layer on the Vycor® substrate could result in the crack geometry changes to influence the static fatigue characteristics.[18]

3.3.1.2 Dynamic Tensile Test

It was necessary to select only fibers having a unimodal flaw distribution with higher Weibull parameter, N, in order to obtain reliable static fatigue data. However, most fibers fabricated by the durable fiber fabrication techniques showed either multimodal flaw distribution or unimodal distribution with a tail, which indicates some degradation of fiber strength. To investigate the effects of preform treatments such as substrate milling process and outside deposition on the strength degradation, SS®-2 rods and standard production graded index preforms were cut into several parts and drawn into fibers after the preform treatments for fabrication of durable fibers. Although the data are scattered, preform treatment processes such as grinding and outside deposition showed a tendency toward strength and fatigue degradation as shown in Table 3-2.

3.3.1.3 Dynamic Fatigue Test

To confirm the N values determined from the static fatigue data, dynamic fatigue tests of selected fibers were also performed at different strain rates. One set of data showed relatively good agreement between the N values obtained from dynamic and static methods. It was apparent that more dynamic fatigue tests are needed at different strain rates to properly determine the N values, but most fiber lengths are too short to complete the test. Furthermore, the median strength determined by dynamic tensile strength is also influenced by the flaw distribution.

3.3.1.4 Other Evaluation Techniques

Both direct and indirect stress measuring techniques were considered to verify the compressive stress level on the fibers. According to literature, photoelastic technique and average strength measurement are the conventional methods to measure the surface compressive stress on glass materials.[4 19] The photoelastic technique was employed to evaluate the compressive stress of the selected fibers. The results are not conclusive. This measurement technique has certain limitations. First, absolute values are not determined directly because they measure only differences in principal stresses. Second, this technique places restrictions on the size and shape of the glass sample because the light path length must be measured accurately. Moreover, the result is not reliable if the glass contains optical inhomegeneities in the form of compositional striae paralled to the surface.[20 21] Therefore, this measurement technique is not totally suitable for measuring surface compressive stress on fibers having a thin compressive layer (i.e. <5 μm) due to a limited optical resolution.[8]

The average measured strength method has met with little favor, mainly because of many parameters affecting the average strength of optical fibers. For example, the 2 m gage length tensile test often showed high data scatter due to association of large flaw distribution resulting in difficulties in relating these measurements on surface-compression fibers to the no-compression fibers.

The additional evaluation technique, in-line compressive stress monitoring technique, as proposed in the revised proposal R77-043, was investigated. This technique was based on the theory of the deflection of a free end beam and did not seem to be feasible to detect small deflection of about 3% due to surface compression on the fiber with variables such as changes in fiber diameter coating thickness and draw speed.[22]

The abraded strength test used by Catholic University was also used to evaluate the surface compression. The results were not promising mainly due to the difficulty in control of degree of abrasion during mechanical stripping of coating material before surface abrasion and testing of such very thin surface layer fibers.

As discussed before, the probability of encountering a more severe flaw increases with surface area (i.e., fiber length) since it occurs with a statistical nature. Therefore, the shortest gage length tests are desirable. These tests should give a sufficient narrow stress distribution so that the surface compression effect could be clearly isolated allowing the comparison of strengths of fibers with compression to those without compression.

Pure bending stress[23] was successfully applied to the minimum constant gage length using a simple device (see Figure 3-1) and this approach is a very promising technique to indirectly measure the compressive stress level on the durable fibers. This technique is simple and reliable by eliminating the uncertainty of gage length effect in the conventional tensile strength tests of optical fibers and the need of longer fiber to complete the test. The results of the pure bending stress tests on the selected durable fibers confirmed the results of experimental compression data determined from the static fatigue test results as shown in Table 2-4.

3.4 Optical Performance

It was assumed that the optical properties of the durable fibers remain unchanged because the basic structure and composition of inner layers such as optical cladding and core were kept constant. It is, however, to be noted that optical performance of these fibers could be altered when fabricated with high residual stresses developed by modifying the surface layer of the fiber. To investigate this effect, several selected fibers longer than 1 km were evaluated; their optical properties and the results are shown in Table 3-4. No significant effect of fiber structure and composition modification on the optical performance was observed when compared to the standard step index fibers.

Table 3-4. Optical Data of Selected Durable Fibers.

Preform No	Length (m)	NA	Dispersion (ns/km)	Attenuation Loss @ 0.85 μm
ES 20763	1387	0.30	7.52	5.57
ES 20781	1032	0.18	2.80	2.84

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Theoretical Model

Based on the developed computer models of stress analysis for the three-layer and four-layer structure fibers, there are three critical structural parameters in fabricating high surface compression fibers. The first one is the thickness of a surface compressive layer which must be as thin as possible to maximize the surface compression. It is believed that the minimum thickness of approximately 1 μm can be sufficient to reduce the static fatique since most submicron-size cracks introduced during the fiber fabrication process initiate the subcritical crack growth resulting in the time-dependent strength degradation.

The other two parameters are the thermal expansion coefficient and glass transition temperature of each glass layer which should be optimized with regard to maximum thermal mismatch between the inner and outer layers during cooling. Therefore, the selection of the glass compositions in each layer is very important for these optimum thermal properties of glass layers. Most importantly, the inner layer glass properties are crucial to increase the thermal stress by the cladding technique. For example, by increasing the thermal expansion coefficient of the core and cladding layers to 3.5×10^{-6}/°C, a surface compression of 0.69 GPa (100 kpsi) should result in a 1-μm thick silica surface layer fiber. However, such a high surface compressive stress structure may have a high probability of failure during the preform fabrication process because of the highly tensile stressed internal layer developed. Therefore, the selection of composition should be compromised with the feasibility of fabrication as well as the optical performance characteristics.

Accurate theoretical prediction of surface compression from the computer model requires actual glass thermal/physical properties in glass fiber form since the properties of glass are governed by thermal history of glass forming processes.

To minimize the contribution of other stress-induced mechanisms as discussed in the previous sections, fiber fabrication process parameters should be held constant during each draw. For example, a minimum drawing tension should be maintained during fiber drawing.

The theoretically predicted stress level should be verified by employing more than one method including either a direct or an indirect stress measuring technique.

4.2 Preform Fabrication

The major conclusion of this contract is that durable fibers with a very thin compressive cladding (<5 μm thickness) of pure silica or Ti-doped silica can and have been fabricated. Data from this project indicate that the center grinding technique may introduce flaws and impurities into the preform surface. It is believed that these defects are subsequently transferred to the drawn fibers, resulting in fibers with both degraded strength and degraded durability characteristics. It is concluded that this substrate removal method by itself is not suitable for the durable fiber program.

Another conclusion of this project is that substrate removal by flame milling is also not a suitable technique for the fabrication of durable fibers. This conclusion was based on the increased warpage observed during the use of the technique. Improvement of the flame milling process was fully addressed in paragraph 3.2.2.2 and should be pursued.

Substrate removal by chemical etching is a viable substrate removal technique using the selected grade substrates. The etching may be used in conjunction with either inside or outside deposition of a compressive layer. The most promising options associated with this technique are as follows:

a. Partial or complete etching of a substrate tube (followed by outside deposition, if necessary)

b. Etching to a barrier layer (followed by outside deposition, if necessary)

c. Etching of precision tubes (followed by outside deposition, if necessary)

In most cases, WG®-2 would be the recommended substrate material unless a barrier layer was employed. If a barrier layer were used, Vycor® or TO®-8 might also be used as a substrate material. However, further investigations are required in the use of acids and buffer solutions before the full potential of the barrier layer method can be evaluated. It is also recommended that either silica or titanium-doped silica be the material used in the compressive layer.

The fabrication of a compressively cladded preform showed that many preforms shattered. They would generally shatter either during internal MCVD process or during the substrate removal process. However, the final surface compressive layer fibers seemed to have relatively fewer shattering problems because the thermal history of fiber forming is quite different from that of preform fabrication. Any residual stress in the fiber can be removed by high temperature annealing (i.e., above Tg) the fiber ends, and the possible difficulty in preparing smooth fiber ends for splicing can be overcome.

A process called vapor axial deposition (VAD) would allow for the fabrication of compressively clad preforms without going through the two shattering prone steps. VAD is a process by which various glasses are deposited axially in the form of soot. The soot is a porous material which can easily withstand the differences in thermal expansion of the various glasses. The soot would later be consolidated into a preform with a compressive layer and drawn into fiber. This process is recommended as a possible method of making fiber with compressive cladding. It should be possible to fabricate compressive cladding at or higher than the 0.69 GPa (100 kpsi) achieved with relatively higher fabrication yield by using this VAD process. In addition to the VAD approach, the feasibility of the compressive cladding technique combined with the hermetic coating method should be studied to increase the fiber durability. The double crucible technique also should be considered as the alternative approach to fabricate a surface compressive fiber with low melting multiple component glasses. The desired thermal properties can be obtained easily from the wide variety of the multicomponent glass compositions so that the triple crucible method instead of the double crucible technique should be developed for the multilayer durable fiber fabrication. The double crucible process is addressed by Beales, et al., British Post Office.[24]

4.3 Evaluation of Compressive Layer Stress

It has been clearly shown that static fatigue resistance of most fibers having a surface compressive layer was improved. This was indicated by an increase in the N values and breaking strengths (at constant time-to-failure) when it was compared to the noncompressive cladded optical fiber. However, studies of long-term durability improvement by the compressive cladding technique should be extended so as to gain a better understanding of stress corrosion mechanisms in various environments.

Surface compressive stresses greater than 100 kpsi (0.69 GPa) were deduced from the static fatigue test results of the fibers having higher thermal expansion coefficients in inner layers with a thin Ti-doped silica surface layer.

Since the photoelastic technique is not totally suitable for measuring surface compressive stress on fibers having a very thin compressive layer, an alternate measurement technique should be employed to determine the compressive stress level on the fiber surface. The alternative measurement technique recommended is the bend testing described in this report.

The bend testing is a simple and reliable stress measuring technique which supported the static fatique test results. Other distinctive methods of compressive stress measurement such as the indentation technique should be evaluated to confirm the results obtained by other techniques.

To achieve better results, in-line proof testing should be performed. The proof testing would truncate the flaw size distribution, thus resulting in a more nearly unimodal strength distribution. Additionally, shorter gage lengths are recommended for both tensile and bending tests. The shorter gage length would also tend to truncate the flaw size distribution for each specimen.

More comprehensive studies of internal stress effects on the optical performance of optical fibers fabricated by the compressive cladding technique should be conducted even though the selected compressive stress fibers did not show significant effects on the optical characteristics of durable fibers.

In summary, this program has demonstrated durability improvement of optical fiber waveguides by employing the compressive cladding technique. However, further refinement work is still needed on the developed fabrication processes of compressive layer fibers. The follow-on program should therefore include more extensive stress analysis such as the basic fracture mechanics (e.g., crack growth) and stress-induced mechanisms in surface compressive layer fibers in addition to the recommended tasks already discussed in this section.

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APPENDIX A

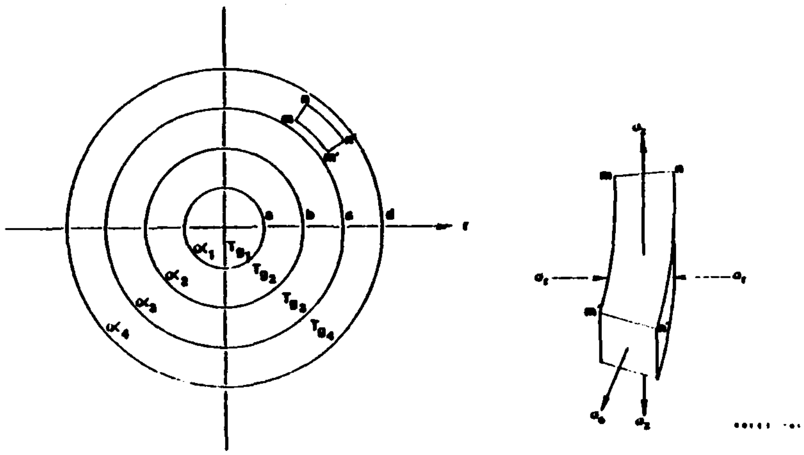
THEORETICAL STRESS ANALYSIS

OF

MULTILAYER OPTICAL FIBERS

A-1.0 INTRODUCTION

Optical fiber waveguides generally consist of several concentric layers of different glass materials having different mechanical and thermal properties. In the typical CVD optical fiber, these layers consist mainly of optical core and cladding layer surrounded by another high silica substrate layer. When a composite structure fiber of this type cools from a temperature above T_g of the glass to ambient temperature, stresses will be developed in the axial direction as well as tangential and radial directions as shown in the following figure.



The thermal stress levels that can be achieved in multilayer optical fiber structures can be theoretically predicted by a mathematical analysis based on the theories of axisymmetric stress and strain equations for a multilayer cylinder. The following stress and strain equations for an nth layer fiber can be written using Hook's Law and Poisson's theorem.

Stresses		Strains
$\sigma_{\theta_1} = A_1$		$\varepsilon_{\theta_1} = \frac{1}{E_1}\left[\sigma_{\theta_1} - \mu_1\left(\sigma_{r_1} + \sigma_{z_1}\right)\right] + \alpha_1 T$
$\sigma_{r_1} = A_1$	First Layer	$\varepsilon_{r_1} = \frac{1}{E_1}\left[\sigma_{r_1} - \mu_1\left(\sigma_{\theta_1} + \sigma_{z_1}\right)\right] + \alpha_1 T$
$\sigma_{z_1} = C_1$		$\varepsilon_{z_1} = \frac{1}{E_1}\left[\sigma_{z_1} - \mu_1\left(\sigma_{\theta_1} + \sigma_{r_1}\right)\right] + \alpha_1 T$
$\sigma_{\theta_2} = A_2 + \frac{B_2}{r^2}$		$\varepsilon_{\theta_1} = \frac{1}{E_2}\left[\sigma_{\theta_2} - \mu_2\left(\sigma_{r_2} + \sigma_{z_2}\right)\right] + \alpha_2 T$
$\sigma_{r_2} = A_2 - \frac{B_2}{r^2}$	Second Layer	$\varepsilon_{r_2} = \frac{1}{E_2}\left[\sigma_{r_2} - \mu_2\left(\sigma_{\theta_2} + \sigma_{z_2}\right)\right] + \alpha_2 T$
$\sigma_{z_2} = C_2$		$\varepsilon_{z_1} = \frac{1}{E_2}\left[\sigma_{z_1} - \mu_2\left(\sigma_{\theta_2} + \sigma_{\theta_2}\right)\right] + \alpha_2 T$
$\vdots$	$\vdots$	$\vdots$
$\sigma_{\theta_n} = A_n - \frac{B_n}{r^2}$		$\varepsilon_{\theta_n} = \frac{1}{E_n}\left[\sigma_{\theta_n} - \mu_n\left(\sigma_{r_n} + \sigma_{z_n}\right)\right] + \alpha_n T$
$\sigma_{r_n} = A_n - \frac{B_n}{r^2}$	nth Layer	$\varepsilon_{r_n} = \frac{1}{E_n}\left[\sigma_{r_n} - \mu_n\left(\sigma_{\theta_n} + \sigma_{z_n}\right)\right] + \alpha_n T$
$\sigma_{z_n} = C_n$		$\varepsilon_{z_n} = \frac{1}{E_n}\left[\sigma_{z_n} - \mu_n\left(\sigma_{\theta_n} + \sigma_{r_n}\right)\right] + \alpha_n T$

Where σ_{θ_n} (ε_{θ_n}), σ_{r_n} (ε_{r_n}), and σ_{z_n} (ε_{θ_n}) are the stress (strain) components in r, θ, and z direction in the nth layer, A_n, B_n, and C_n are constants. E_n, μ_n, and α_n are Young's modulus, Poisson's ratio, and thermal expansion coefficient in the nth layer material respectively, and T is the temperature.

Using the following simplifying assumptions and boundary conditions depending on the actual thermal properties of glass layer materials, 8 simultaneous stress (strain) equations for three-layer fibers and 11 equations for four-layer fibers were derived and solved by a computer. (These equations are listed in detail in the following section.)

Assumptions:

Material properties: $E_1 = E_2 = \ldots . E_n$, $\mu_2 = \ldots \mu_n$

$$\frac{1-2\mu_n}{E_n} = \frac{1}{3\ K_n}\ ,\ \alpha^* \underset{\sim}{\sim} 3\ \alpha, K^* \sim 0.5\ K$$

where K is bulk modulus and asterisk designates glass properties above the glass transition temperature (T_g).

<u>General boundary conditions</u>:

Equality of σ_r at layer boundary

$\sigma_r = \sigma_\theta = \sigma_z$ at or above T_g

$\sigma_r = o$ at the free boundary

No net force in z direction

Equality of ε_z at layer boundary

In order to maximize the surface compression, the surface layer must contain the glass with the lowest α and the highest T_g. Several cases of cooling sequence can be considered to analyze thermal stresses, depending on the T_g of inner layer glasses. However based on the current optical fiber glass systems, only one case for each fiber structure was considered as shown in the following sections.

The total axial stress of the surface layer is the sum of each thermal stress constant (i.e., C_3 and C_4 in three-layer and four-layer model, respectively) computed by solving the simultaneous equations. The examples of numerical computation are shown in Appendix B.

Three-Layer Model

Case: $T_{g_3} > T_{g_1} > T_{g_2}$

A. Cooling from T_{g_3} to T_{g_1}, $\Delta T = T_{g_3} - T_{g_1}$

The stresses in the first and second layers must be hydrostatic

$$\sigma_{r_1} = \sigma_{z_1} = \sigma_{\theta_1}, \; C_1 = A_1$$

$$\varepsilon_{r_1} = \varepsilon_{z_1} = \varepsilon_{\theta_1} = \frac{C_1}{3K_1^*} + \alpha_1 \, T_1$$

$$\sigma_{r_2} = \sigma_{z_2} = \sigma_{\theta_2}, \; C_2 = A_2, \quad B_2 = 0$$

$$\varepsilon_{r_2} = \varepsilon_{z_2} = \varepsilon_{\theta_2} = \frac{C_2}{3K_1^*} + \alpha_2 \, T_2 \qquad K^* = 0.5K$$

Boundary Conditions:

1. $\sigma_{r_3} = 0$ at $r = c$, $\qquad A_3 - \frac{B_3}{c^2} = 0$

2. $\sigma_{r_3} = \sigma_{r_2}$ at $r = b$, $\qquad C_2 - (\frac{1}{c^2} - \frac{1}{b^2}) \, B_3 = 0$

3. No net forces in the axial direction

$$a^2 C_1 = (b^2 - a^2) \, C_2 + (c^2 - b^2) \, C_3 = 0$$

4. $\varepsilon_{z_2} = \varepsilon_{z_3}$, at $r = b$

$$\frac{C_2}{3K^*} - \frac{C_3 - 2\mu A_3}{E} = \Delta\alpha_3 \Delta T \qquad \Delta\alpha_3 = \alpha_3 - 3\alpha_2$$

5. $\varepsilon_{z_1} = \varepsilon_{z_2}$ at $r = a$

$$\frac{C_1}{3K^*} - \frac{C_2}{3K^*} = \Delta\alpha_2\Delta T \qquad \Delta\alpha_2\Delta T = 3(\alpha_2-\alpha_1)$$

B. Cooling from T_{g_1} to T_{g_2}, $\Delta T = T_{g_1} - T_{g_2}$

The stresses in the second layer are hydrostatic

$$\sigma_{r_2} = \sigma_{z_2} = \sigma_{\theta_2}, \; C_2 = A_2, \quad B_2 = 0$$

$$\varepsilon_{r_2} = \varepsilon_{z_2} = \varepsilon_{\theta_2} = \frac{C_2}{3K^*_2} + \alpha_2 T_2$$

Boundary Conditions:

1. $\sigma_{r_3} = 0$ at $r = c$, $\qquad A_3 - \frac{B_3}{c^2} = 0$

2. $\sigma_{r_1} = \sigma_{r_2}$ at $r = a$ $\qquad A_1 = C_2 \qquad A_1 = A_2$

3. $A^2C_1 + (b^2-a^2)\,C_2 + (c^2-b^2)\,C_3 = 0$

4. $\varepsilon_{z_1} = \varepsilon_{z_2}$ at $r = a$

$$\frac{C_1}{E} - \frac{2\mu}{E} C_2 = \Delta\alpha_2{}^*\Delta T \qquad \Delta\alpha_2{}^* = 3\alpha_2-\alpha_1$$

5. $\sigma_{r_3} = \sigma_{r_2}$ at $r = b$ $\qquad C_2 - (\frac{1}{c^2} - \frac{1}{b^2})\,B_3 = 0$

6. $\sigma_{z_2} = \sigma_{z_3}$ at $r = b$

$$\frac{C_2}{3K} - \frac{C_3}{E} + \frac{2\mu A_3}{E} = \Delta\alpha_3{}^*\Delta T \qquad \Delta\alpha_3{}^* = \alpha_3 - 3\alpha_3$$

C. Cooling from T_{g_2} to T_o (room temp) $\Delta_T = T_{g_2} - T_o$

1. At the free boundary the stress normal to the boundary must vanish: $\sigma_{r_3} = 0$ at $r = c$

$$A_3 - \frac{B_3}{c^2} = 0 \text{ - } (1)$$

2. $\sigma_{r_3} = \sigma_{r_2}$ at $r = b$

$$A_2 - \frac{B_2}{b^2} = \left(\frac{1}{c^2} - \frac{1}{b^2}\right) B_3 = 0 \text{ - - - - - - - - - - - - - - - - - } (2)$$

3. $\sigma_{r_2} = \sigma_{r_1}$ at $r = a$

$$A_1 - A_2 + \frac{B_2}{a^2} = 0 \text{ - } (3)$$

4. The condition of no net force in the axial direction

$$a^2C_1 = (b^2-a^2)\, C_2 + (c^2-b^2)\, C_3 = 0 \text{ - - - - - - - - - - - - - - } 4$$

5. $\varepsilon_{\theta_1} = \varepsilon_{\theta_2}$ at $r = a$ $\qquad E_1 = E_2 \qquad \Delta\alpha_2 = \alpha''_2 - \alpha_2$

$$(1-\mu)\, A_1 - \mu C_1 - (1-\mu)\, A_2 - \frac{(1+\mu)}{a^2} B_2 + \mu C_2 = E\Delta\alpha_2\Delta T \text{ - - - } (5)$$

6. $\varepsilon_{\theta_2} = \varepsilon_{\theta_3}$ at $r = b$ $\quad E_2 = E_3 \quad \Delta\alpha_3 = \alpha_3 - \alpha_2$

$$(1-\mu)\ A_2 + \frac{(1+\mu)}{b^2} B_2 - \mu C_2 - (1-\mu)\ A_3 - \frac{(1+\mu)}{b^2} B_2 + \mu C_3 = E\Delta\alpha_3\Delta T \text{ - - - - - } (6)$$

7. $\varepsilon_{z_1} = \varepsilon_{z_2}$ at $r = a$ $\quad C_1 - \frac{2\mu}{a^2} B_2 - C_2 = E\Delta\alpha_2\ \Delta T$ - - (7)

8. $\varepsilon_{z_2} = \varepsilon_{z_3}$ at $r = b$ $\quad C_2 - 2\mu A_2 - C_3 + 3\mu A_3 = E\Delta\alpha_3\Delta T$ - (8)

Four-Layer Model

Case: $\quad T_{g_4} > T_{g_3} > T_{g_1} > T_{g_2}$

A. Cooling from T_{g_4} to T_{g_3}, $\Delta T = T_{g_4} - T_{g_3}$

All layers except outer layer (4th layer) are hydrostatic

$\sigma_{r_1} = \sigma_{z_2} = \sigma_{\theta_1} \qquad C_1 = A_1$

$$\varepsilon_{r_1} = \varepsilon_{z_1} = \varepsilon_{\theta_1} = \frac{C_1}{3K^*_1} + \alpha_1 T_1$$

$\sigma_{r_2} = \sigma_{z_2} = \sigma_{\theta_2} \qquad C_2 = A_2 \qquad B_2 = 0$

$$\varepsilon_{r_2} = \varepsilon_{z_2} = \varepsilon_{\theta_2} = \frac{C_2}{3K^*_2} + \alpha_2 T_2$$

$\sigma_{r_3} = \sigma_{z_3} = \sigma_{\theta_3} \qquad C_3 = A_3 \qquad B_3 = 0$

Boundary Conditions:

1. $\sigma_{r_4} = 0$ at $r = d$

$$A_r - \frac{B_4}{d^2} = 0 \qquad\qquad A_r = \frac{B_4}{d^2}$$

2. $\sigma_{r_3} = \sigma_{r_4}$ at $r = c$

$$C_3 - \left(\frac{1}{d^2} - \frac{1}{c^2}\right) B_4 = 0$$

3. No net force in z direction

$$a^2C_1 + (b^2 - a^2)C_2 + (c^{2'} - b^2)\ C_3 + (d^2 - c^2)C_4 = 0$$

4. $\varepsilon_{r_3} = \varepsilon_{r_4}$ at $r = c$

$$\frac{C_3}{3K^*_3} - \left(\frac{C_4 - 3\mu A_4}{E}\right) = \Delta\alpha_4 \Delta T$$

$$\Delta\alpha_4 = \alpha_4 = 3\alpha_3$$

5. $\alpha_{r_3} = \alpha_{r_2}$ at $r = b$ $\qquad C_3 - C_2 = 0$

6. $\sigma_{r_2} = \sigma_{r_1}$ at $r = a$ $\qquad C_2 - C_1 = 0$

ASSUMPTIONS = $K_1^* = K_2^* = K_3^*$

B. Cooling from T_{g_3} to T_{g_1}, $\Delta T = T_{g_3} - T_{g_1}$

only first and second layers are hydrostatic

$$\sigma_{r_1} = \sigma_{z_1} - \sigma_{\theta_1} \qquad C_1 = A_1$$

$$\varepsilon_{r_1} = \varepsilon_{z_1} = \varepsilon_{\theta_1} = \frac{C_1}{3K_1^*} + \alpha_1 T_1$$

$$\sigma_{r_2} = \sigma_{z_2} = \sigma_{\theta_2} \qquad C_2 = A_2, \qquad B_2 = 0$$

$$\varepsilon_{r_2} = \varepsilon_{z_2} = \varepsilon_{\theta_2} = \frac{C_2}{3K_2^*} + \alpha_2 T_2$$

Boundary Conditions:

1. $\sigma_{r_4} = 0$ at $r = d$

$$A_4 - \frac{B_4}{d^2} = 0 \qquad A_4 = \frac{B_4}{d^2}$$

2. $\sigma_{r_3} = \sigma_{r_4}$ at $r = c$

$$A_3 - \frac{B_3}{c^2} - \left(\frac{1}{d^2} - \frac{1}{c^2}\right) B_4 = 0$$

3. $\sigma_{r_2} = \sigma_{r_3}$ at $r = b$

$$C_2 - A_3 + \frac{B_3}{c^2} = 0$$

4. $\sigma_{r_1} = \sigma_{r_2}$ at $r = a$

$$C_2 - C_1 = 0$$

5. $\varepsilon_{z_3} = \varepsilon_{z_4}$ at $r = c$

$$C_3 - 2\mu A_3 - C_4 + 3\mu A_4 = E\Delta\alpha_4\Delta T, \text{ where } \Delta\alpha_4 = \alpha_4 - \alpha_3$$

6. No net force in z direction

$$a^2 C_1 + (b^2-A^2) C_2 + (c^2-b^2) C_3 + (d^2-c^2) C_4 = 0$$

7. $\varepsilon_{r_3} = \varepsilon_{r_2}$ at $r = b$

$$\frac{C_2}{3K_2^*} - \frac{(1-\mu)A_3}{E} + \left(\frac{1+\mu}{Eb^2}\right) B_3 + \frac{\mu}{E} C_3 = \Delta\alpha_3\Delta T \text{ where } \Delta\alpha_3 = \alpha_3 - 3\alpha_2$$

8. $\varepsilon_{\theta_3} = \varepsilon_{\theta_4}$ at $r = c$

$$A_3 (1-\mu) - A_4 (1-\mu) + B_3 \frac{(1+\mu)}{c^2} - B_4 \left(\frac{1+\mu}{c^2}\right) - \mu C_3 + \mu_4 = E\Delta\alpha_4\Delta T$$

where $\Delta\alpha_4 = \alpha_4 - \alpha_3$

C. Cooling from T_{g_1} to T_{g_2} the second layer is hydrostatic

$$\sigma_{z_2} = \sigma_{r_2} = \sigma_{\theta_2} \qquad C_2 = A_2 \qquad B_2 = 0$$

$$\varepsilon_{z_2} = \varepsilon_{r_2} = \varepsilon_{\theta_2} = \frac{C_2}{3K_2^*} + \alpha_2 T_2$$

Boundary Conditions:

1. $\sigma_{r_4} = 0$ at $r = d$ $\qquad A_4 - \frac{B_4}{d^2} = 0$

2. $\sigma_{r_3} = \sigma_{r_4}$ at $r = c$

$$A_3 - \frac{B_3}{c^2} - \left(\frac{1}{d^2} - \frac{1}{c^2}\right) B_4 = 0$$

3. No net force in z direction

$$a^2 C_1 + (b^2 - a^2)\ C_2 + (c^2 - b^2)\ C3 + (d^2 - c^2)\ C_4 = 0$$

4. $\sigma_{r_3} = \sigma_{r_2}$ at $r = b$ $\qquad C_2 - A_3 + \frac{B_3}{b^2} = 0$

5. $\sigma_{r_2} = \theta_{r_1}$ at $4 = a$ $\qquad C_2 - A_1 = 0$

6. $\varepsilon_{z_3} = \varepsilon_{z_4}$ at $r = c$

$$C_3 - 2\mu A_3 - C_4 - 3\mu A_4 = E\Delta\alpha_4 \Delta T, \qquad \Delta\alpha_4 = \alpha_4 - \alpha_3$$

7. $\varepsilon_{z_3} = \varepsilon_{z_2}$ at $r = b$

$$\frac{C_2}{3K_2^*} - \frac{C_3 - 3\mu A_3}{E} = \Delta\alpha_3 \Delta T, \qquad \Delta\alpha_3 = \alpha_3 - 3\alpha_2$$

8. $\varepsilon_{z_2} = \varepsilon_{z_1}$ at $r = a$

$$\frac{C_1 - 3\mu A_1}{E} - \frac{C_2}{3K_2^*} = \Delta\alpha_2 \Delta T, \qquad \Delta\alpha_2 = 3\alpha_2 - \alpha_1$$

9. $\varepsilon_{\theta_3} = \varepsilon_{\theta_4}$ at $r = c$

$$A_3\ (1-\mu) - A_4\ (1-\mu) + B_3\ \left(\frac{1+\mu}{c^2}\right) - B_4\ \left(\frac{1+\mu}{c^2}\right) - \mu C_3 + \ldots\ldots..$$

$$\mu_4 = E\Delta\alpha_4 \Delta T \qquad \Delta\alpha_4 = \alpha_4 - \alpha_3$$

D. Cooling from T_{g_2} to T_o, $\Delta T = T_{g_2} - T_o$

All layers are solid state

1. $\sigma_{r_4} = 0$ at $r = d$ $\qquad A_4 = \frac{B_4}{d^2} = 0$

2. $\sigma_{r_4} = \sigma_{r_2}$ at $r = c$ $\qquad A_3 - \frac{B_3}{c^2} + B_4(\frac{1}{d^2} - \frac{1}{c^2}) = 0$

3. $\sigma_{r_3} = \sigma_{r_2}$ at $r = b$ $\qquad A_2 - A_3 + \frac{1}{b^2} B_2 - \frac{1}{b^2} B_3 = 0$

4. $\sigma_{r_2} = \sigma_{r_1}$ at $r = a$ $\qquad A_1 + A_2 - \frac{B_2}{a^2} = 0$

5. No net force in Z-direction

$$a^2C_1 + (b^2-a^2)\ C_2 + (c^2-b^2)\ C_3 + (d^2-c^2)\ C_4 = 0$$

6. $\varepsilon_{\theta_1} = \varepsilon_{\theta_2}$ at $r = a$

$$(1-\mu)\ A_1 - (1-\mu)\ A_2 - \frac{(1+\mu)}{a^2}\ B_2 - \mu C_1 + \mu_1 C_2 =$$

$$E\Delta\alpha_2\Delta T_2 \text{ where } \Delta\alpha_2 = (\alpha_2 = \alpha_1)$$

7. $\varepsilon_{\theta_2} = \varepsilon_{\theta_3}$ at $r = b$

$$(1-\mu)\ A_2 - (1-\mu)\ A_3 + \frac{(1+\mu)}{b^2}\ B_3 - \mu C_2 + \mu_1 C_3 =$$

$$E\Delta\alpha_3\Delta T \text{ where } \Delta\nabla_3 = \nabla_3 - \alpha_2$$

8. $\varepsilon_{\theta_3} = \varepsilon_{\theta_4}$ at $r = c$

$$(1-\mu)\ A_3 - (1-\mu)\ A_4 + \frac{(1+\mu)}{c^2} B_4 - \mu C_3 - \mu C_4 =$$

$$E\Delta\alpha_4\Delta T \text{ where } \Delta\alpha_4 = \alpha_4 - \alpha_3$$

9. $\varepsilon_{z_1} = \varepsilon_{z_2} =$ at $r = a$

$$\frac{2\mu}{a^2} B_2 + C_1 - C_2 = E\Delta\alpha_2\Delta T \text{ where } \Delta\alpha_2 = \alpha_2 - \alpha_1$$

10. $\varepsilon_{z_2} = \varepsilon_{z_3}$ at $r = b$

$$-2\mu\ A_2 + 2\mu\ A_3 + C_2 - C_3 = E\Delta\alpha_3\Delta T \text{ where } \Delta\alpha_3 = \alpha_3 - \alpha_2$$

11. $\varepsilon_{z_3} = \varepsilon_{z_4}$ at $r = c$

$$-2\mu\ A_3 + 3\mu A_4 + C_3 - C_4 = E\Delta\alpha_4\Delta T \text{ where } \Delta\alpha_4 = \alpha_4 - \alpha_3$$

APPENDIX B

COMPUTER MODEL PROGRAMS

B-1.0 THREE LAYER SOLUTION

The following is an illustration of a typical solution for a theoretical three-layer compressive layer calculation. The amount of compression in the outer layer of this example is 30.71 kpsi (0.21 GPa). This value is arrived at by adding the three eighth-solution values together (i.e., 0.196302E+05 + 0.109455E+05 + 0.129586E+05 = 0.307502E+05). This solution was performed on an IBM 370/138 computer.

```
const456 consteva data1 m1 cntl m2 cntl m3 cntl t

EXECUTION BEGINS...
ENTER A,B,C,ALPHA1,ALPHA2,ALPHA3,TG1,TG2,TG3,T0,E,K,     MUE,ISIZE
EXECUTION BEGINS...
ENTER A,B,C,ALPHA1,ALPHA2,ALPHA3,TG1,TG2,TG3,T0,E,K,     MUE,ISIZE
EXECUTION BEGINS...
ENTER A,B,C,ALPHA1,ALPHA2,ALPHA3,TG1,TG2,TG3,T0,E,K,     MUE,ISIZE
R;

soln m1 cntl t

EXECUTION BEGINS...
SOLUTION VALUES
 1               0.0
 2               0.0
 3               0.196241E+05
 4               0.0
 5               0.120689E+00
 6              -0.204689E+04
 7              -0.204689E+04
 8               0.196302E+05
EXECUTION TERMINATED
R;

soln m2 cntl t

EXECUTION BEGINS...
SOLUTION VALUES
 1              -0.169335E+04
 2              -0.169335E+04
 3               0.162346E+05
 4               0.0
 5               0.998438E-01
 6               0.847809E+03
 7              -0.169335E+04
 8               0.109455E+05
EXECUTION TERMINATED
R;

soln m3 cntl t

EXECUTION BEGINS...
SOLUTION VALUES
 1              -0.338300E+04
 2               0.754102E+02
 3               0.647890E+04
 4               0.418492E-02
 5               0.398457E-01
 6              -0.676558E+04
 7               0.151375E+03
```

```
 8              0.129586E+05
EXECUTION TERMINATED
R;
```

The following files were used in the solution of the previously mentioned theoretical three-layer compressive layer calculation. Files CONST456 EXEC and SOLN EXEC are executives used to call other files and control the solution.

Files C4, C5, C6, SOLN, MATIN, MXOUT, SIMQ and LOC are FORTRAN source listings use in the execution of the solution.

File CONSTEVA DATA 1 is the file where the particular data used in the solution are stored.

```
&CONTROL OFF NOMSG
GLOBAL TXTLIB FORTMOD2 MOD2EEH MOD2NEEH CMSLIB
FILE FT05F001 DISK &1 &2
FILE FT06F001 TERM
FILE FT07F001 DISK &3 &4 (LRECL 80 BLOCK 800 RECFM FB
LOAD C4
START
FILE FT05F001 DISK &1 &2
FILE FT06F001 TERM
FILE FT07F001 DISK &5 &6 (LRECL 80 BLOCK 800 RECFM FB
LOAD C5
START
FILE FT05F001 DISK &1 &2
FILE FT06F001 TERM
FILE FT07F001 DISK &7 &8 (LRECL 80 BLOCK 800 RECFM FB
LOAD C6
START
```

```
      REAL M,N,MUE,K
      DIMENSION N(11)
      DIMENSION M(11,11)
      WRITE(6,2)
 2    FORMAT(' ENTER A,B,C,ALPHA1,ALPHA2,ALPHA3,TG1,TG2,TG3,T0,E,K,
     CMUE,ISIZE')
      READ (5,*) A,B,C,ALPHA1,ALPHA2,ALPHA3,TG1,TG2,TG3,T0,E
      READ (5,*) K,MUE,ISIZE
      M(1,1)=1.0
      M(1,2)=0.0
      M(1,3)=0.0
      M(1,4)=0.0
      M(1,5)=0.0
      M(1,6)=0.0
      M(1,7)=0.0
      M(1,8)=0.0
      M(2,1)=1.0
      M(2,2)=1.0
      M(2,3)=0.0
      M(2,4)=0.0
      M(2,5)=0.0
      M(2,6)=0.0
      M(2,7)=0.0
      M(2,8)=0.0
      M(3,1)=0.0
      M(3,2)=0.0
      M(3,3)=1.0
      M(3,4)=0.0
      M(3,5)=-1/C**2
      M(3,6)=0.0
      M(3,7)=0.0
      M(3,8)=0.0
      M(4,1)=1.0
      M(4,2)=1.0
      M(4,3)=0.0
      M(4,4)=1.0
      M(4,5)=0.0
      M(4,6)=0.0
      M(4,7)=0.0
      M(4,8)=0.0
      M(5,1)=0.0
      M(5,2)=0.0
      M(5,3)=0.0
      M(5,4)=0.0
      M(5,5)=-(1/C**2-1/B**2)
      M(5,6)=0.0
      M(5,7)=1.0
      M(5,8)=0.0
      M(6,1)=0.0
      M(6,2)=0.0
      M(6,3)=0.0
      M(6,4)=0.0
      M(6,5)=0.0
      M(6,6)=A**2
      M(6,7)=(B**2-A**2)
```

```
      M(6,8)=(C**2-B**2)
      M(7,1)=0.0
      M(7,2)=0.0
      M(7,3)=2*MUE/E
      M(7,4)=0.0
      M(7,5)=0.0
      M(7,6)=0.0
      M(7,7)=(1/(1.5*K))
      M(7,8)=-1/E
      M(8,1)=0.0
      M(8,2)=0.0
      M(8,3)=0.0
      M(8,4)=0.0
      M(8,5)=0.0
      M(8,6)=1.0
      M(8,7)=-1.0
      M(8,8)=0.0
      I=9
      N(1)=0.0
      N(2)=0.0
      N(3)=0.0
      N(4)=0.0
      N(5)=0.0
      N(6)=0.0
      N(7)=((TG3-TG1)*(ALPHA3-3*ALPHA2))
      N(8)=0.0
      WRITE(7,10) ISIZE,ISIZE
   10 FORMAT('  9999',2I4)
      DO 200 J=1,ISIZE
      WRITE(7,11)  (M(J,K1),K1=1,7)
   11 FORMAT(7E10.4)
      WRITE(7,12)  (M(J,K1),K1=8,11)
   12 FORMAT(4E10.4)
  200 CONTINUE
      WRITE(7,13) I
   13 FORMAT(I1)
      WRITE(7,11)  (N(K1),K1=1,7)
      WRITE(7,12)  (N(K1),K1=8,11)
      WRITE(7,14)
   14 FORMAT(80(' '))
      STOP
      END
```

```
      REAL M,N,MUE,K
      DIMENSION N(11)
      DIMENSION M(11,11)
      WRITE(6,2)
    2 FORMAT(' ENTER A,B,C,ALPHA1,ALPHA2,ALPHA3,TG1,TG2,TG3,TO,E,K,
     CMUE,ISIZE')
      READ (5,*) A,B,C,ALPHA1,ALPHA2,ALPHA3,TG1,TG2,TG3,TO,E
      READ (5,*) K,MUE,ISIZE
C5    FORMAT (10E5.5)
      M(1,1)=0.0
      M(1,2)=0.0
      M(1,3)=1.0
      M(1,4)=0.0
      M(1,5)=-1/C**2
      M(1,6)=0.0
      M(1,7)=0.0
      M(1,8)=0.0
      M(2,1)=0.0
      M(2,2)=1.0
      M(2,3)=0.0
      M(2,4)=0.0
      M(2,5)=0.0
      M(2,6)=0.0
      M(2,7)=-1.0
      M(2,8)=0.0
      M(3,1)=1.0
      M(3,2)=0.0
      M(3,3)=0.0
      M(3,4)=0.0
      M(3,5)=0.0
      M(3,6)=0.0
      M(3,7)=-1.0
      M(3,8)=0.0
      M(4,1)=0.0
      M(4,2)=0.0
      M(4,3)=0.0
      M(4,4)=1.0
      M(4,5)=0.0
      M(4,6)=0.0
      M(4,7)=0.0
      M(4,8)=0.0
      M(5,1)=0.0
      M(5,2)=0.0
      M(5,3)=0.0
      M(5,4)=0.0
      M(5,5)=0.0
      M(5,6)=A**2
      M(5,7)=(B**2-A**2)
      M(5,8)=(C**2-B**2)
      M(6,1)=-(2*MUE/E)
      M(6,2)=0.0
      M(6,3)=0.0
      M(6,4)=0.0
      M(6,5)=0.0
      M(6,6)=+(1/E)
```

```
      M(6,7)=-(1/(1.5*K))
      M(6,8)=0.0
      M(7,1)=0.0
      M(7,2)=0.0
      M(7,3)=0.0
      M(7,4)=0.0
      M(7,5)=-(1/C**2-1/B**2)
      M(7,6)=0.0
      M(7,7)=1.0
      M(7,8)=0.0
      M(8,1)=0.0
      M(8,2)=0.0
      M(8,3)=(2*MUE/E)
      M(8,4)=0.0
      M(8,5)=0.0
      M(8,6)=0.0
      M(8,7)=(1/(1.5*K))
      M(8,8)=-1/E
      I=9
      N(1)=0.0
      N(2)=0.0
      N(3)=0.0
      N(4)=0.0
      N(5)=0.0
      N(6)=((3*ALPHA2-ALPHA1)*(TG1-TG2))
      N(7)=0.0
      N(8)=((ALPHA3-3*ALPHA2)*(TG1-TG2))
      WRITE(7,10) ISIZE,ISIZE
   10 FORMAT('  9999',2I4)
      DO 200 J=1,ISIZE
      WRITE(7,11) (M(J,K1),K1=1,7)
   11 FORMAT(7E10.4)
      WRITE(7,12) (M(J,K1),K1=8,11)
   12 FORMAT(4E10.4)
  200 CONTINUE
      WRITE(7,13) I
   13 FORMAT(I1)
      WRITE(7,11) (N(K1),K1=1,7)
      WRITE(7,12) (N(K1),K1=8,11)
      WRITE(7,14)
   14 FORMAT(80(' '))
      STOP
      END
```

```
      REAL M,N,MUE,K
      DIMENSION N(11)
      DIMENSION M(11,11)
      WRITE(6,2)
    2 FORMAT(' ENTER A,B,C,ALPHA1,ALPHA2,ALPHA3,TG1,TG2,TG3,TO,E,K,
     CMUE,ISIZE')
      READ (5,*) A,B,C,ALPHA1,ALPHA2,ALPHA3,TG1,TG2,TG3,TO,E
      READ (5,*) K,MUE,ISIZE
C5    FORMAT (10E5.5)
      M(1,1)=0.0
      M(1,2)=0.0
      M(1,3)=1.0
      M(1,4)=0.0
      M(1,5)=-1/C**2
      M(1,6)=0.0
      M(1,7)=0.0
      M(1,8)=0.0
      M(2,1)=0.0
      M(2,2)=1.0
      M(2,3)=0.0
      M(2,4)=-1/B**2
      M(2,5)=(1/B**2-1/C**2)
      M(2,6)=0.0
      M(2,7)=0.0
      M(2,8)=0.0
      M(3,1)=1.0
      M(3,2)=-1.0
      M(3,3)=0.0
      M(3,4)=1/A**2
      M(3,5)=0.0
      M(3,6)=0.0
      M(3,7)=0.0
      M(3,8)=0.0
      M(4,1)=0.0
      M(4,2)=0.0
      M(4,3)=0.0
      M(4,4)=0.0
      M(4,5)=0.0
      M(4,6)=A**2
      M(4,7)=(B**2-A**2)
      M(4,8)=(C**2-B**2)
      M(5,1)=(1-MUE)
      M(5,2)=-(1-MUE)
      M(5,3)=0.0
      M(5,4)=-(1+MUE)/A**2
      M(5,5)=0.0
      M(5,6)=-MUE
      M(5,7)=MUE
      M(5,8)=0.0
      M(6,1)=0.0
      M(6,2)=1-MUE
      M(6,3)=-(1-MUE)
      M(6,4)=(1+MUE)/B**2
      M(6,5)=-(1+MUE)/B**2
      M(6,6)=0.0
```

```
      M(6,7)=-MUE
      M(6,8)=MUE
      M(7,1)=0.0
      M(7,2)=0.0
      M(7,3)=0.0
      M(7,4)=+(2*MUE/A**2)
      M(7,5)=0.0
      M(7,6)=1.0
      M(7,7)=-1.0
      M(7,8)=0.0
      M(8,1)=0.0
      M(8,2)=-2*MUE
      M(8,3)=2*MUE
      M(8,4)=0.0
      M(8,5)=0.0
      M(8,6)=0.0
      M(8,7)=1.0
      M(8,8)=-1.0
      I=9
      N(1)=0.0
      N(2)=0.0
      N(3)=0.0
      N(4)=0.0
      N(5)=E*(ALPHA2-ALPHA1)*(TG2-T0)
      N(6)=E*(ALPHA3-ALPHA2)*(TG2-T0)
      N(7)=E*(ALPHA2-ALPHA1)*(TG2-T0)
      N(8)=E*(ALPHA3-ALPHA2)*(TG2-T0)
      WRITE(7,10) ISIZE,ISIZE
   10 FORMAT('  9999',2I4)
      DO 200 J=1,ISIZE
      WRITE(7,11)  (M(J,K1),K1=1,7)
   11 FORMAT(7E10.4)
      WRITE(7,12)  (M(J,K1),K1=8,11)
   12 FORMAT(4E10.4)
  200 CONTINUE
      WRITE(7,13) I
   13 FORMAT(I1)
      WRITE(7,11)  (N(K1),K1=1,7)
      WRITE(7,12)  (N(K1),K1=8,11)
      WRITE(7,14)
   14 FORMAT(80(' '))
      STOP
      END
```

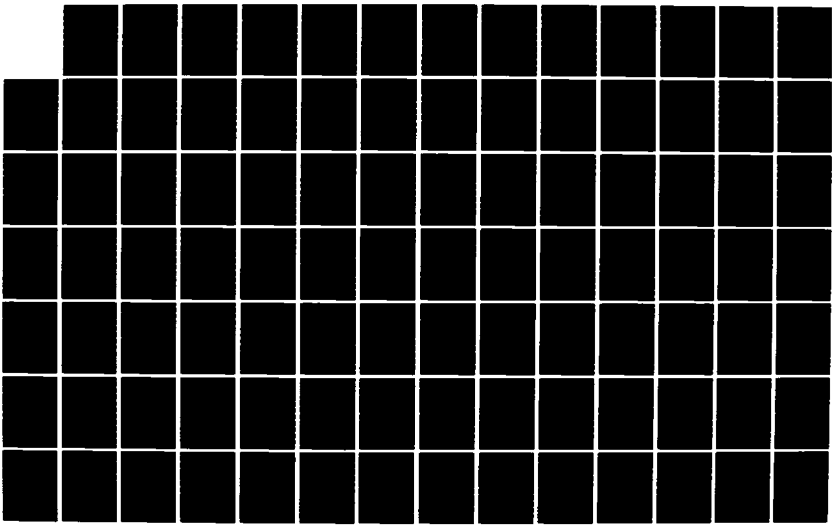
```
&CONTROL OFF
GLOBAL TXTLIB FORTMOD2 MOD2EEH MOD2NEEH CMSLIB
&IF &3 = P &GOTO -A
&IF &3 = T &GOTO -B
-C
FILEDEF FT05F001 DISK &1 &2
LOAD SOLN
START
&EXIT
-A
FILEDEF FT06F001 PRINTER
&GOTO -C
-B
FILEDEF FT06F001 TERM
&GOTO -C
```

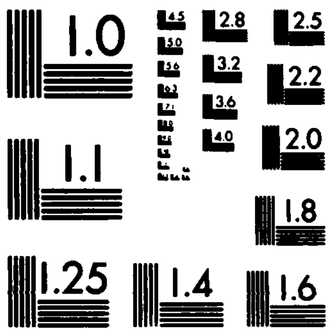
```
C       PROGRAM NAME -- SOLN
        DIMENSION A(121),B(11)
10      FORMAT(1H1,34HSOLUTION OF SIMULTANEOUS EQUATIONS)
11      FORMAT(1H0,44HDIMENSIONED AREA TOO SMALL FOR INPUT MATRIX,I4)
12      FORMAT(1H0,20HEXECUTION TERMINATED)
13      FORMAT(1H0,47HROW AND COLUMN DIMENSIONS NOT EQUAL FOR MATRIX,I4)
14      FORMAT(1H0,42HINCORRECT NUMBER OF DATA CARDS FOR MATRIX,I4)
15      FORMAT(1H0,18HGO ON TO NEXT CASE)
16      FORMAT(1H0,38HSTRUCTURE CODE IS NOT ZERO FOR MATRIX,I4)
17      FORMAT(1H1,17HORIGINAL B VECTOR,////)
18      FORMAT(1H1,15HSOLUTION VALUES,////)
19      FORMAT(1H0,18HMATRIX IS SINGULAR)
20      FORMAT(7F10.0)
21      FORMAT(I3,10X,E16.6)
22      FORMAT(1H0,11HEND OF CASE)
C       WRITE (6,10)
25      CALL MATIN(ICOD,A,121,N,M,MS,IER)
        IF(N) 30,95,30
30      IF(IER-1)45,35,40
35      WRITE(6,11) ICOD
        GO TO 90
40      WRITE(6,14) ICOD
        GO TO 95
45      IF(N-M) 50,55,50
50      WRITE(6,13) ICOD
        GO TO 90
55      IF(MS) 60,65,60
60      WRITE(6,16)ICOD
        GO TO 90
65      CALL MXOUT(ICOD,A,N,M,MS,60,120,2)
C
C       ADDED END=98 TO STOP READING PAST END OF FILE CONDITION
C
C       READ(5,*,END=98) (B(I),I=1,N)
        READ(5,20,END=98) (B(I),I=1,N)
C       WRITE(6,17)
C       DO 70 I=1,N
C       WRITE(6,21) I,B(I)
C 70    CONTINUE
        CALL SIMQ(A,B,N,KS)
        IF(KS-1) 80,75,80
75      WRITE(6,19)
        WRITE(6,15)
        GO TO 25
80      WRITE(6,18)
        DO 85 I=1,N
        WRITE(6,21) I,B(I)
85      CONTINUE
C       WRITE(6,22)
        GO TO 25
C
C       ADDED END=98 TO STOP READING PAST END OF FILE ERROR CONDITION
C
C0      READ(5,*,END=98) (B(I),I=1,N)
90      READ(5,20,END=98) (B(I),I=1,N)
```

AD-A132 909 HIGH STRENGTH LONG LENGTH OPTICAL FIBERS INCREASED DURABILITY OF OPTICAL..(U) ITT ELECTRO-OPTICAL PRODUCTS DIV ROANOKE VA P H PRIDEAUX ET AL. 01 NOV 80

2/3

UNCLASSIFIED N00123-79-C-0301 F/G 11/5 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

```
      WRITE(6,15)
      GO TO 25
95    WRITE(6,12)
 98   STOP
      END
```

```
      SUBROUTINE MXOUT (ICODE,A,N,M,MS,LINS,IPOS,ISP)
      DIMENSION A(1),B(8)
1     FORMAT(1H1,5X, 7HMATRIX ,I5,6X,I3,5H ROWS,6X,I3,8H COLUMNS,
     18X,13HSTORAGE MODE ,I1,8X,5HPAGE ,I2,/)
2     FORMAT(12X,8HCOLUMN  ,7(3X,I3,10X))
3     FORMAT(1H )
4     FORMAT(1H ,7X,4HROW ,I3,7(E16.6))
5     FORMAT(1H0,7X,4HROW ,I3,7(E16.6))
      J=1
      NEND=IPOS/16-1
      LEND=(LINS/ISP)-2
      IPAGE=1
10    LSTRT=1
C20   WRITE(6,1) ICODE,N,M,MS,IPAGE
20    CONTINUE
      JNT=J+NEND-1
      IPAGE=IPAGE+1
31    IF(JNT-M) 33,33,32
32    JNT=M
33    CONTINUE
C     WRITE(6,2) (JCUR,JCUR=J,JNT)
      IF(ISP-1) 35,35,40
C35   WRITE(6,3)
35    CONTINUE
40    LTEND=LSTRT+LEND-1
      DO 80 L=LSTRT,LTEND
      DO 55 K=1,NEND
      KK=K
      JT = J+K-1
      CALL LOC(L,JT,IJNT,N,M,MS)
      B(K)=0.0
      IF(IJNT) 50,50,45
45    B(K)=A(IJNT)
50    CONTINUE
      IF(JT-M) 55,60,60
55    CONTINUE
C60   IF(ISP-1)65,65,70
60    IF(ISP-1)75,75,75
65    WRITE(6,4) L,(B(JW),JW=1,KK)
      GO TO 75
70    WRITE(6,5) L,(B(JW),JW=1,KK)
75    IF(N-L) 85,85,80
80    CONTINUE
      LSTRT=LSTRT+LEND
      GO TO 20
85    IF(JT-M) 90,95,95
90    J=JT+1
      GO TO 10
95    RETURN
      END
```

```
      SUBROUTINE MATIN(ICODE,  A,ISIZE,IROW,ICOL,IS,IER)
      DIMENSION A(1)
      DIMENSION CARD(8)
1     FORMAT(7F10.0)
2     FORMAT(I6,2I4,I2)
      IDC=7
      IER=0
      READ( 5,2,END=40)ICODE,IROW,ICOL,IS
      CALL LOC(IROW,ICOL,ICNT,IROW,ICOL,IS)
      IF(ISIZE-ICNT) 6,7,7
6     IER=1
7     IF  (ICNT) 38,38,8
8     ICOLT=ICOL
      IROCR=1
11    IRCDS=(ICOLT-1)/IDC+1
      IF(IS-1) 15,15,12
12    IRCDS=1
15    DO 31 K=1,IRCDS
      READ(5,1,END=40) (CARD(I),I=1,IDC)
      IF(IER) 16,16,31
16    L=0
      JS=(K-1)*IDC+ICOL-ICOLT+1
      JE=JS+IDC-1
      IF(IS-1) 19,19,17
17    JE=JS
19    DO 30 J=JS,JE
      IF(J-ICOL) 20,20,31
20    CALL LOC(IROCR ,J,IJ,IROW,ICOL,IS)
      L=L+1
30    A(IJ)=CARD(L)
31    CONTINUE
      IROCR=IROCR+1
      IF(IROW-IROCR)  38,35,35
35    IF(IS-1) 37,36,36
36    ICOLT=ICOLT-1
37    GO TO 11
38    READ(5,1,END=40)  CARD(1)
      IF(CARD(1)-9.E9) 39,40,39
39    IER=2
40    RETURN
      END
```

```
C
C     ..................................................................
C
C        SUBROUTINE SIMQ
C
C        PURPOSE
C           OBTAIN SOLUTION OF A SET OF SIMULTANEOUS LINEAR EQUATIONS,
C           AX=B
C
C        USAGE
C           CALL SIMQ(A,B,N,KS)
C
C        DESCRIPTION OF PARAMETERS
C           A - MATRIX OF COEFFICIENTS STORED COLUMNWISE.  THESE ARE
C               DESTROYED IN THE COMPUTATION.  THE SIZE OF MATRIX A IS
C               N BY N.
C           B - VECTOR OF ORIGINAL CONSTANTS (LENGTH N). THESE ARE
C               REPLACED BY FINAL SOLUTION VALUES, VECTOR X.
C           N - NUMBER OF EQUATIONS AND VARIABLES. N MUST BE .GT. ONE.
C           KS - OUTPUT DIGIT
C                0 FOR A NORMAL SOLUTION
C                1 FOR A SINGULAR SET OF EQUATIONS
C
C        REMARKS
C           MATRIX A MUST BE GENERAL.
C           IF MATRIX IS SINGULAR , SOLUTION VALUES ARE MEANINGLESS.
C           AN ALTERNATIVE SOLUTION MAY BE OBTAINED BY USING MATRIX
C           INVERSION (MINV) AND MATRIX PRODUCT (GMPRD).
C
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C           NONE
C
C        METHOD
C           METHOD OF SOLUTION IS BY ELIMINATION USING LARGEST PIVOTAL
C           DIVISOR. EACH STAGE OF ELIMINATION CONSISTS OF INTERCHANGING
C           ROWS WHEN NECESSARY TO AVOID DIVISION BY ZERO OR SMALL
C           ELEMENTS.
C           THE FORWARD SOLUTION TO OBTAIN VARIABLE N IS DONE IN
C           N STAGES. THE BACK SOLUTION FOR THE OTHER VARIABLES IS
C           CALCULATED BY SUCCESSIVE SUBSTITUTIONS. FINAL SOLUTION
C           VALUES ARE DEVELOPED IN VECTOR B, WITH VARIABLE 1 IN B(1),
C           VARIABLE 2 IN B(2),........, VARIABLE N IN B(N).
C           IF NO PIVOT CAN BE FOUND EXCEEDING A TOLERANCE OF 0.0,
C           THE MATRIX IS CONSIDERED SINGULAR AND KS IS SET TO 1. THIS
C           TOLERANCE CAN BE MODIFIED BY REPLACING THE FIRST STATEMENT.
C
C     ..................................................................
C
      SUBROUTINE SIMQ(A,B,N,KS)
      DIMENSION A(1),B(1)
C
C        FORWARD SOLUTION
C
      TOL=0.0
      KS=0
```

```
      JJ=-N
      DO 65 J=1,N
      JY=J+1
      JJ=JJ+N+1
      BIGA=0
      IT=JJ-J
      DO 30 I=J,N
C
C        SEARCH FOR MAXIMUM COEFFICIENT IN COLUMN
C
      IJ=IT+I
      IF(ABS(BIGA)-ABS(A(IJ))) 20,30,30
   20 BIGA=A(IJ)
      IMAX=I
   30 CONTINUE
C
C        TEST FOR PIVOT LESS THAN TOLERANCE (SINGULAR MATRIX)
C
      IF(ABS(BIGA)-TOL) 35,35,40
   35 KS=1
      RETURN
C
C        INTERCHANGE ROWS IF NECESSARY
C
   40 I1=J+N*(J-2)
      IT=IMAX-J
      DO 50 K=J,N
      I1=I1+N
      I2=I1+IT
      SAVE=A(I1)
      A(I1)=A(I2)
      A(I2)=SAVE
C
C        DIVIDE EQUATION BY LEADING COEFFICIENT
C
   50 A(I1)=A(I1)/BIGA
      SAVE=B(IMAX)
      B(IMAX)=B(J)
      B(J)=SAVE/BIGA
C
C        ELIMINATE NEXT VARIABLE
C
      IF(J-N) 55,70,55
   55 IQS=N*(J-1)
      DO 65 IX=JY,N
      IXJ=IQS+IX
      IT=J-IX
      DO 60 JX=JY,N
      IXJX=N*(JX-1)+IX
      JJX=IXJX+IT
   60 A(IXJX)=A(IXJX)-(A(IXJ)*A(JJX))
   65 B(IX)=B(IX)-(B(J)*A(IXJ))
C
C        BACK SOLUTION
C
```

```
   70 NY=N-1
      IT=N*N
      DO 80 J=1,NY
      IA=IT-J
      IB=N-J
      IC=N
      DO 80 K=1,J
      B(IB)=B(IB)-A(IA)*B(IC)
      IA=IA-N
   80 IC=IC-1
      RETURN
      END
```

```
C
C     ..................................................................
C
C        SUBROUTINE LOC
C
C        PURPOSE
C           COMPUTE A VECTOR SUBSCRIPT FOR AN ELEMENT IN A MATRIX OF
C           SPECIFIED STORAGE MODE
C
C        USAGE
C           CALL LOC (I,J,IR,N,M,MS)
C
C        DESCRIPTION OF PARAMETERS
C           I    - ROW NUMBER OF ELEMENT
C           J    - COLUMN NUMBER  OF ELEMENT
C           IR   - RESULTANT VECTOR SUBSCRIPT
C           N    - NUMBER OF ROWS IN MATRIX
C           M    - NUMBER OF COLUMNS IN MATRIX
C           MS   - ONE DIGIT NUMBER FOR STORAGE MODE OF MATRIX
C                   0 - GENERAL
C                   1 - SYMMETRIC
C                   2 - DIAGONAL
C
C        REMARKS
C           NONE
C
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C           NONE
C
C        METHOD
C           MS=0    SUBSCRIPT IS COMPUTED FOR A MATRIX WITH N*M ELEMENTS
C                   IN STORAGE (GENERAL MATRIX)
C           MS=1    SUBSCRIPT IS COMPUTED FOR A MATRIX WITH N*(N+1)/2 IN
C                   STORAGE (UPPER TRIANGLE OF SYMMETRIC MATRIX). IF
C                   ELEMENT IS IN LOWER TRIANGULAR PORTION, SUBSCRIPT IS
C                   CORRESPONDING ELEMENT IN UPPER TRIANGLE.
C           MS=2    SUBSCRIPT IS COMPUTED FOR A MATRIX WITH N ELEMENTS
C                   IN STORAGE (DIAGONAL ELEMENTS OF DIAGONAL MATRIX).
C                   IF ELEMENT IS NOT ON DIAGONAL (AND THEREFORE NOT IN
C                   STORAGE), IR IS SET TO ZERO.
C
C     ..................................................................
C
      SUBROUTINE LOC(I,J,IR,N,M,MS)
C
      IX=I
      JX=J
      IF(MS-1) 10,20,30
   10 IRX=N*(JX-1)+IX
      GO TO 36
   20 IF(IX-JX) 22,24,24
   22 IRX=IX+(JX*JX-JX)/2
      GO TO 36
   24 IRX=JX+(IX*IX-IX)/2
      GO TO 36
```

```
   30 IRX=0
      IF(IX-JX) 36,32,36
   32 IRX=IX
   36 IR=IRX
      RETURN
      END
```

```
1.10E-3,2.36E-3,2.48E-3,2.31E-6,1.50E-6,.00E-6,865,700,1200,25,1.05E7
5E6,0.17,8
```

B-2.0 FOUR-LAYER SOLUTION

The following is an illustration of a typical solution for a typical four-layer compressive layer calculation. The amount of compression in the outer layer of this example is 29.0 kpsi (0.2 GPa). This value is arrived at by adding together all the eleventh-solution values (i.e., 0.129981E+05 + 0.606770E+03 + 0.250532E+04 + 0.128861E+05 = 0.289963E+05).

This solution was performed on an IBM 370/138 computer.

```
co891011 co891011 data1 m1 cntl m2 cntl m3 cntl m4 cntl t

EXECUTION BEGINS...
ENTER A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4,
      TG1,TG2,TG3,TG4,TO,E,K,MUE,ISIZE
EXECUTION BEGINS...
ENTER A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4,
      TG1,TG2,TG3,TG4,TO,E,K,MUE,ISIZE
EXECUTION BEGINS...
ENTER A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4,
      TG1,TG2,TG3,TG4,TO,E,K,MUE,ISIZE
EXECUTION BEGINS...
ENTER A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4,
      TG1,TG2,TG3,TG4,TO,E,K,MUE,ISIZE
R;

soln2 m1 cntl m2 cntl m3 cntl m4 cntl t

EXECUTION BEGINS...
SOLUTION VALUES
 1              0.0
 2              0.0
 3              0.0
 4              0.129976E+05
 5              0.0
 6              0.0
 7              0.812351E-01
 8             -0.542325E+04
 9             -0.542325E+04
10             -0.542325E+04
11              0.129981E+05
EXECUTION TERMINATED

EXECUTION BEGINS...
SOLUTION VALUES
 1              0.0
 2              0.0
 3             -0.150393E+03
 4              0.292390E+03
 5              0.0
 6             -0.125189E-03
 7              0.182744E-02
 8             -0.122000E+03
 9             -0.122000E+03
10             -0.278776E+03
11              0.606770E+03
EXECUTION TERMINATED

EXECUTION BEGINS...
SOLUTION VALUES
 1             -0.131200E+04
 2              0.0
 3             -0.416697E+03
```

```
 4            0.135441E+04
 5            0.0
 6            0.654461E-03
 7            0.846506E-02
 8           -0.932306E+03
 9           -0.131200E+04
10           -0.103686E+04
11            0.250532E+04
EXECUTION TERMINATED

EXECUTION BEGINS...
SOLUTION VALUES
 1           -0.271091E+05
 2           -0.214858E+05
 3            0.333798E+03
 4            0.918896E+04
 5            0.242699E-02
 6            0.183770E-01
 7            0.574310E-01
 8           -0.127601E+05
 9           -0.151335E+04
10           -0.482470E+04
11            0.128861E+05
EXECUTION TERMINATED
R;
```

The following files were used in the solution of the theoretical four-layer compressive layer calculation. Files CO891011 EXEC and SOLN2 EXEC are executives which call other files and control the particular solution.

Files CONSTEV8, CONSTEV9, CONSTE10, and CONSTE11 are FORTRAN source listings called by executive CO891011.

Files SOLN, MATIN, MXOUT, SIMQ, and LOC are called by executive SOLN2 and are listed in the three-layer solution section of this appendix.

File CO891011 DATA 1 is the file where the particular data used in this solution are stored.

```
&CONTROL OFF NOMSG
GLOBAL TXTLIB FORTMOD2 MOD2EEH MOD2NEEH CMSLIB
FILE FT05F001 DISK &1 &2
FILE FT06F001 TERM
FILE FT07F001 DISK &3 &4 (LRECL 80 BLOCK 800 RECFM FB
LOAD CONSTEV8
START
FILE FT05F001 DISK &1 &2
FILE FT06F001 TERM
FILE FT07F001 DISK &5 &6 (LRECL 80 BLOCK 800 RECFM FB
LOAD CONSTEV9
START
FILE FT05F001 DISK &1 &2
FILE FT06F001 TERM
FILE FT07F001 DISK &7 &8 (LRECL 80 BLOCK 800 RECFM FB
LOAD CONSTE10
START
FILE FT05F001 DISK &1 &2
FILE FT06F001 TERM
FILE FT07F001 DISK &9 &10(LRECL 80 BLOCK 800 RECFM FB
LOAD CONSTE11
START
```

```
      REAL M,N,MUE,K
      DIMENSION N(11)
      DIMENSION M(11,11)
      WRITE(6,2)
    2 FORMAT(' ENTER A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4,
     CTG1,TG2,TG3,TG4,T0,E,K,MUE,ISIZE')
      READ (5,*) A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4
      READ (5,*) TG1,TG2,TG3,TG4,T0,E,K,MUE,ISIZE
C5    FORMAT (10E5.5)
      M(1,1)=0.0
      M(1,2)=0.0
      M(1,3)=0.0
      M(1,4)=1.0
      M(1,5)=0.0
      M(1,6)=0.0
      M(1,7)=-(1/(D**2))
      M(1,8)=0.0
      M(1,9)=0.0
      M(1,10)=0.0
      M(1,11)=0.0
      M(2,1)=0.0
      M(2,2)=0.0
      M(2,3)=0.0
      M(2,4)=0.0
      M(2,5)=0.0
      M(2,6)=0.0
      M(2,7)=-(1/D**2-1/C**2)
      M(2,8)=0.0
      M(2,9)=0.0
      M(2,10)=1.0
      M(2,11)=0.0
      M(3,1)=0.0
      M(3,2)=0.0
      M(3,3)=0.0
      M(3,4)=0.0
      M(3,5)=0.0
      M(3,6)=0.0
      M(3,7)=0.0
      M(3,8)=A**2
      M(3,9)=(B**2-A**2)
      M(3,10)=(C**2-B**2)
      M(3,11)=(D**2-C**2)
      M(4,1)=0.0
      M(4,2)=0.0
      M(4,3)=0.0
      M(4,4)=((2*MUE)/E)
      M(4,5)=0.0
      M(4,6)=0.0
      M(4,7)=0.0
      M(4,8)=0.0
      M(4,9)=0.0
      M(4,10)=(1/(1.5*K))
      M(4,11)=-(1/E)
      M(5,1)=0.0
      M(5,2)=0.0
```

```
      M(5,3)=0.0
      M(5,4)=0.0
      M(5,5)=0.0
      M(5,6)=0.0
      M(5,7)=0.0
      M(5,8)=0.0
      M(5,9)=1.0
      M(5,10)=-1.0
      M(5,11)=0.0
      M(6,1)=0.0
      M(6,2)=0.0
      M(6,3)=0.0
      M(6,4)=0.0
      M(6,5)=0.0
      M(6,6)=0.0
      M(6,7)=0.0
      M(6,8)=-1.0
      M(6,9)=1.0
      M(6,10)=0.0
      M(6,11)=0.0
      M(7,1)=1.0
      M(7,2)=0.0
      M(7,3)=0.0
      M(7,4)=0.0
      M(7,5)=0.0
      M(7,6)=0.0
      M(7,7)=0.0
      M(7,8)=0.0
      M(7,9)=0.0
      M(7,10)=0.0
      M(7,11)=0.0
      M(8,1)=1.0
      M(8,2)=1.0
      M(8,3)=0.0
      M(8,4)=0.0
      M(8,5)=0.0
      M(8,6)=0.0
      M(8,7)=0.0
      M(8,8)=0.0
      M(8,9)=0.0
      M(8,10)=0.0
      M(8,11)=0.0
      M(9,1)=1.0
      M(9,2)=1.0
      M(9,3)=1.0
      M(9,4)=0.0
      M(9,5)=0.0
      M(9,6)=0.0
      M(9,7)=0.0
      M(9,8)=0.0
      M(9,9)=0.0
      M(9,10)=0.0
      M(9,11)=0.0
      M(10,1)=0.0
      M(10,2)=0.0
```

```
      M(10,3)=0.0
      M(10,4)=0.0
      M(10,5)=1.0
      M(10,6)=0.0
      M(10,7)=0.0
      M(10,8)=0.0
      M(10,9)=0.0
      M(10,10)=0.0
      M(10,11)=0.0
      M(11,1)=0.0
      M(11,2)=0.0
      M(11,3)=0.0
      M(11,4)=0.0
      M(11,5)=1.0
      M(11,6)=1.0
      M(11,7)=0.0
      M(11,8)=0.0
      M(11,9)=0.0
      M(11,10)=0.0
      M(11,11)=0.0
      I=9
      N(1)=0.0
      N(2)=0.0
      N(3)=0.0
      N(4)=(ALPHA4-3*ALPHA3)*(TG4-TG3)
      N(5)=0.0
      N(6)=0.0
      N(7)=0.0
      N(8)=0.0
      N(9)=0.0
      N(10)=0.0
      N(11)=0.0
      WRITE(7,10) ISIZE,ISIZE
   10 FORMAT('  9999',2I4)
      DO 200 J=1,ISIZE
      WRITE(7,11) (M(J,K1),K1=1,7)
   11 FORMAT(7E10.4)
      WRITE(7,12) (M(J,K1),K1=8,11)
   12 FORMAT(4E10.4)
  200 CONTINUE
      WRITE(7,13) I
   13 FORMAT(I1)
      WRITE(7,11) (N(K1),K1=1,7)
      WRITE(7,12) (N(K1),K1=8,11)
      WRITE(7,14)
   14 FORMAT(30(' '))
      STOP
      END
```

```
      REAL M,N,MUE,K
      DIMENSION N(11)
      DIMENSION M(11,11)
      WRITE(6,2)
    2 FORMAT(' ENTER A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4,
     CTG1,TG2,TG3,TG4,T0,E,K,MUE,ISIZE')
      READ (5,*) A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4
      READ (5,*) TG1,TG2,TG3,TG4,T0,E,K,MUE,ISIZE
C5    FORMAT (10E5.5)
      M(1,1)=0.0
      M(1,2)=0.0
      M(1,3)=0.0
      M(1,4)=1.0
      M(1,5)=0.0
      M(1,6)=0.0
      M(1,7)=-(1/(D**2))
      M(1,8)=0.0
      M(1,9)=0.0
      M(1,10)=0.0
      M(1,11)=0.0
      M(2,1)=0.0
      M(2,2)=0.0
      M(2,3)=1.0
      M(2,4)=0.0
      M(2,5)=0.0
      M(2,6)=-(1/(C**2))
      M(2,7)=-(1/D**2-1/C**2)
      M(2,8)=0.0
      M(2,9)=0.0
      M(2,10)=0.0
      M(2,11)=0.0
      M(3,1)=0.0
      M(3,2)=0.0
      M(3,3)=-1.0
      M(3,4)=0.0
      M(3,5)=0.0
      M(3,6)=(1/(C**2))
      M(3,7)=0.0
      M(3,8)=0.0
      M(3,9)=1.0
      M(3,10)=0.0
      M(3,11)=0.0
      M(4,1)=0.0
      M(4,2)=0.0
      M(4,3)=0.0
      M(4,4)=0.0
      M(4,5)=0.0
      M(4,6)=0.0
      M(4,7)=0.0
      M(4,8)=1.0
      M(4,9)=-1.0
      M(4,10)=0.0
      M(4,11)=0.0
      M(5,1)=0.0
      M(5,2)=0.0
```

```
      M(5,3)=-(2*MUE)
      M(5,4)=2*MUE
      M(5,5)=0.0
      M(5,6)=0.0
      M(5,7)=0.0
      M(5,8)=0.0
      M(5,9)=0.0
      M(5,10)=1.0
      M(5,11)=-1.0
      M(6,1)=0.0
      M(6,2)=0.0
      M(6,3)=0.0
      M(6,4)=0.0
      M(6,5)=0.0
      M(6,6)=0.0
      M(6,7)=0.0
      M(6,8)=A**2
      M(6,9)=(B**2-A**2)
      M(6,10)=(C**2-B**2)
      M(6,11)=(D**2-C**2)
      M(7,1)=0.0
      M(7,2)=0.0
      M(7,3)=-((1-MUE)/E)
      M(7,4)=0.0
      M(7,5)=0.0
      M(7,6)=((1+MUE)/(E*(B**2)))
      M(7,7)=0.0
      M(7,8)=0.0
      M(7,9)=(1/(1.5*K))
      M(7,10)=(MUE/E)
      M(7,11)=0.0
      M(8,1)=0.0
      M(8,2)=0.0
      M(8,3)=(1-MUE)
      M(8,4)=-(1-MUE)
      M(8,5)=0.0
      M(8,6)=((1+MUE)/(C**2))
      M(8,7)=-((1+MUE)/(C**2))
      M(8,8)=0.0
      M(8,9)=0.0
      M(8,10)=-MUE
      M(8,11)=MUE
      M(9,1)=1.0
      M(9,2)=0.0
      M(9,3)=0.0
      M(9,4)=0.0
      M(9,5)=0.0
      M(9,6)=0.0
      M(9,7)=0.0
      M(9,8)=0.0
      M(9,9)=0.0
      M(9,10)=0.0
      M(9,11)=0.0
      M(10,1)=1.0
      M(10,2)=1.0
```

```
      M(10,3)=0.0
      M(10,4)=0.0
      M(10,5)=0.0
      M(10,6)=0.0
      M(10,7)=0.0
      M(10,8)=0.0
      M(10,9)=0.0
      M(10,10)=0.0
      M(10,11)=0.0
      M(11,1)=1.0
      M(11,2)=1.0
      M(11,3)=0.0
      M(11,4)=0.0
      M(11,5)=1.0
      M(11,6)=0.0
      M(11,7)=0.0
      M(11,8)=0.0
      M(11,9)=0.0
      M(11,10)=0.0
      M(11,11)=0.0
      I=9
      N(1)=0.0
      N(2)=0.0
      N(3)=0.0
      N(4)=0.0
      N(5)=E*(ALPHA4-ALPHA3)*(TG3-TG1)
      N(6)=0.0
      N(7)=(ALPHA3-3*ALPHA2)*(TG3-TG1)
      N(8)=E*(ALPHA4-ALPHA3)*(TG3-TG1)
      N(9)=0.0
      N(10)=0.0
      N(11)=0.0
      WRITE(7,10) ISIZE,ISIZE
   10 FORMAT('  9999',2I4)
      DO 200 J=1,ISIZE
      WRITE(7,11) (M(J,K1),K1=1,7)
   11 FORMAT(7E10.4)
      WRITE(7,12) (M(J,K1),K1=8,11)
   12 FORMAT(4E10.4)
  200 CONTINUE
      WRITE(7,13) I
   13 FORMAT(I1)
      WRITE(7,11) (N(K1),K1=1,7)
      WRITE(7,12) (N(K1),K1=8,11)
      WRITE(7,14)
   14 FORMAT(80(' '))
      STOP
      END
```

```
      REAL M,N,MUE,K
      DIMENSION N(11)
      DIMENSION M(11,11)
      WRITE(6,2)
    2 FORMAT(' ENTER A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4,
     CTG1,TG2,TG3,TG4,T0,E,K,MUE,ISIZE')
      READ (5,*) A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4
      READ (5,*) TG1,TG2,TG3,TG4,T0,E,K,MUE,ISIZE
C5    FORMAT (10E5.5)
      M(1,1)=0.0
      M(1,2)=0.0
      M(1,3)=0.0
      M(1,4)=1.0
      M(1,5)=0.0
      M(1,6)=0.0
      M(1,7)=-(1/(D**2))
      M(1,8)=0.0
      M(1,9)=0.0
      M(1,10)=0.0
      M(1,11)=0.0
      M(2,1)=0.0
      M(2,2)=0.0
      M(2,3)=1.0
      M(2,4)=0.0
      M(2,5)=0.0
      M(2,6)=-(1/(C**2))
      M(2,7)=-(1/D**2-1/C**2)
      M(2,8)=0.0
      M(2,9)=0.0
      M(2,10)=0.0
      M(2,11)=0.0
      M(3,1)=0.0
      M(3,2)=0.0
      M(3,3)=0.0
      M(3,4)=0.0
      M(3,5)=0.0
      M(3,6)=0.0
      M(3,7)=0.0
      M(3,8)=A**2
      M(3,9)=(B**2-A**2)
      M(3,10)=(C**2-B**2)
      M(3,11)=(D**2-C**2)
      M(4,1)=0.0
      M(4,2)=0.0
      M(4,3)=-1.0
      M(4,4)=0.0
      M(4,5)=0.0
      M(4,6)=(1/(B**2))
      M(4,7)=0.0
      M(4,8)=0.0
      M(4,9)=1.0
      M(4,10)=0.0
      M(4,11)=0.0
      M(5,1)=-1.0
      M(5,2)=0.0
```

```
      M(5,3)=0.0
      M(5,4)=0.0
      M(5,5)=0.0
      M(5,6)=0.0
      M(5,7)=0.0
      M(5,8)=0.0
      M(5,9)=1.0
      M(5,10)=0.0
      M(5,11)=0.0
      M(6,1)=0.0
      M(6,2)=0.0
      M(6,3)=-2*MUE
      M(6,4)=2*MUE
      M(6,5)=0.0
      M(6,6)=0.0
      M(6,7)=0.0
      M(6,8)=0.0
      M(6,9)=0.0
      M(6,10)=1.0
      M(6,11)=-1.0
      M(7,1)=0.0
      M(7,2)=0.0
      M(7,3)=((2*MUE)/E)
      M(7,4)=0.0
      M(7,5)=0.0
      M(7,6)=0.0
      M(7,7)=0.0
      M(7,8)=0.0
      M(7,9)=(1/(1.5*K))
      M(7,10)=-(1/E)
      M(7,11)=0.0
      M(8,1)=-((2*MUE)/(E))
      M(8,2)=0.0
      M(8,3)=0.0
      M(8,4)=0.0
      M(8,5)=0.0
      M(8,6)=0.0
      M(8,7)=0.0
      M(8,8)=1/E
      M(8,9)=-(1/(1.5*K))
      M(8,10)=0.0
      M(8,11)=0.0
      M(9,1)=0.0
      M(9,2)=0.0
      M(9,3)=(1-MUE)
      M(9,4)=-(1-MUE)
      M(9,5)=0.0
      M(9,6)=((1+MUE)/(C**2))
      M(9,7)=-((1+MUE)/(C**2))
      M(9,8)=0.0
      M(9,9)=0.0
      M(9,10)=-MUE
      M(9,11)=MUE
      M(10,1)=0.0
      M(10,2)=1.0
```

```
      M(10,3)=0.0
      M(10,4)=0.0
      M(10,5)=0.0
      M(10,6)=0.0
      M(10,7)=0.0
      M(10,8)=0.0
      M(10,9)=0.0
      M(10,10)=0.0
      M(10,11)=0.0
      M(11,1)=0.0
      M(11,2)=1.0
      M(11,3)=0.0
      M(11,4)=0.0
      M(11,5)=1.0
      M(11,6)=0.0
      M(11,7)=0.0
      M(11,8)=0.0
      M(11,9)=0.0
      M(11,10)=0.0
      M(11,11)=0.0
      I=9
      N(1)=0.0
      N(2)=0.0
      N(3)=0.0
      N(4)=0.0
      N(5)=0.0
      N(6)=E*(ALPHA4-ALPHA3)*(TG1-TG2)
      N(7)=(ALPHA3-3*ALPHA2)*(TG1-TG2)
      N(8)=(3*ALPHA2-ALPHA1)*(TG1-TG2)
      N(9)=E*(ALPHA4-ALPHA3)*(TG1-TG2)
      N(10)=0.0
      N(11)=0.0
      WRITE(7,10) ISIZE,ISIZE
   10 FORMAT('  9999',2I4)
      DO 200 J=1,ISIZE
      WRITE(7,11) (M(J,K1),K1=1,7)
   11 FORMAT(7E10.4)
      WRITE(7,12) (M(J,K1),K1=8,11)
   12 FORMAT(4E10.4)
  200 CONTINUE
      WRITE(7,13) I
   13 FORMAT(I1)
      WRITE(7,11) (N(K1),K1=1,7)
      WRITE(7,12) (N(K1),K1=8,11)
      WRITE(7,14)
   14 FORMAT(80(' '))
      STOP
      END
```

```
      REAL M,N,MUE,K
      DIMENSION N(11)
      DIMENSION M(11,11)
      WRITE(6,2)
    2 FORMAT(' ENTER A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4,
     CTG1,TG2,TG3,TG4,T0,E,K,MUE,ISIZE')
      READ (5,*) A,B,C,D,ALPHA1,ALPHA2,ALPHA3,ALPHA4
      READ (5,*) TG1,TG2,TG3,TG4,T0,E,K,MUE,ISIZE
C5    FORMAT (10E5.5)
      M(1,1)=0.0
      M(1,2)=0.0
      M(1,3)=0.0
      M(1,4)=1.0
      M(1,5)=0.0
      M(1,6)=0.0
      M(1,7)=-(1/(D**2))
      M(1,8)=0.0
      M(1,9)=0.0
      M(1,10)=0.0
      M(1,11)=0.0
      M(2,1)=0.0
      M(2,2)=0.0
      M(2,3)=-1.0
      M(2,4)=0.0
      M(2,5)=0.0
      M(2,6)=(1/(C**2))
      M(2,7)=(1/D**2-1/C**2)
      M(2,8)=0.0
      M(2,9)=0.0
      M(2,10)=0.0
      M(2,11)=0.0
      M(3,1)=0.0
      M(3,2)=-1.0
      M(3,3)=1.0
      M(3,4)=0.0
      M(3,5)=(1/(B**2))
      M(3,6)=-(1/(B**2))
      M(3,7)=0.0
      M(3,8)=0.0
      M(3,9)=0.0
      M(3,10)=0.0
      M(3,11)=0.0
      M(4,1)=-1.0
      M(4,2)=1.0
      M(4,3)=0.0
      M(4,4)=0.0
      M(4,5)=-(1/(A**2))
      M(4,6)=0.0
      M(4,7)=0.0
      M(4,8)=0.0
      M(4,9)=0.0
      M(4,10)=0.0
      M(4,11)=0.0
      M(5,1)=0.0
      M(5,2)=0.0
```

```
      M(5,3)=0.0
      M(5,4)=0.0
      M(5,5)=0.0
      M(5,6)=0.0
      M(5,7)=0.0
      M(5,8)=A**2
      M(5,9)=(B**2-A**2)
      M(5,10)=(C**2-B**2)
      M(5,11)=(D**2-C**2)
      M(6,1)=(1-MUE)
      M(6,2)=-(1-MUE)
      M(6,3)=0.0
      M(6,4)=0.0
      M(6,5)=-((1+MUE)/(A**2))
      M(6,6)=0.0
      M(6,7)=0.0
      M(6,8)=-MUE
      M(6,9)=MUE
      M(6,10)=0.0
      M(6,11)=0.0
      M(7,1)=0.0
      M(7,2)=(1-MUE)
      M(7,3)=-(1-MUE)
      M(7,4)=0.0
      M(7,5)=0.0
      M(7,6)=((1+MUE)/(B**2))
      M(7,7)=0.0
      M(7,8)=0.0
      M(7,9)=-(MUE)
      M(7,10)=MUE
      M(7,11)=0.0
      M(8,1)=0.0
      M(8,2)=0.0
      M(8,3)=(1-MUE)
      M(8,4)=-(1-MUE)
      M(8,5)=0.0
      M(8,6)=((1+MUE)/(C**2))
      M(8,7)=-((1+MUE)/(C**2))
      M(8,8)=0.0
      M(8,9)=0.0
      M(8,10)=-MUE
      M(8,11)=MUE
      M(9,1)=0.0
      M(9,2)=0.0
      M(9,3)=0.0
      M(9,4)=0.0
      M(9,5)=((2*MUE)/(A**2))
      M(9,6)=0.0
      M(9,7)=0.0
      M(9,8)=1.0
      M(9,9)=-1.0
      M(9,10)=0.0
      M(9,11)=0.0
      M(10,1)=0.0
      M(10,2)=-(2*MUE)
```

```
      M(10,3)=2*MUE
      M(10,4)=0.0
      M(10,5)=0.0
      M(10,6)=0.0
      M(10,7)=0.0
      M(10,8)=0.0
      M(10,9)=1.0
      M(10,10)=-1.0
      M(10,11)=0.0
      M(11,1)=0.0
      M(11,2)=0.0
      M(11,3)=-(2*MUE)
      M(11,4)=2*MUE
      M(11,5)=0.0
      M(11,6)=0.0
      M(11,7)=0.0
      M(11,8)=0.0
      M(11,9)=0.0
      M(11,10)=1.0
      M(11,11)=-1.0
      I=9
      N(1)=0.0
      N(2)=0.0
      N(3)=0.0
      N(4)=0.0
      N(5)=0.0
      N(6)=(E*(ALPHA2-ALPHA1)*(TG2-T0))
      N(7)=(E*(ALPHA3-ALPHA2)*(TG2-T0))
      N(8)=(E*(ALPHA4-ALPHA3)*(TG2-T0))
      N(9)=(E*(ALPHA2-ALPHA1)*(TG2-T0))
      N(10)=(E*(ALPHA3-ALPHA2)*(TG2-T0))
      N(11)=(E*(ALPHA4-ALPHA3)*(TG2-T0))
      WRITE(7,10) ISIZE,ISIZE
   10 FORMAT('  9999',2I4)
      DO 200 J=1,ISIZE
      WRITE(7,11) (M(J,K1),K1=1,7)
   11 FORMAT(7E10.4)
      WRITE(7,12) (M(J,K1),K1=8,11)
   12 FORMAT(4E10.4)
  200 CONTINUE
      WRITE(7,13) I
   13 FORMAT(I1)
      WRITE(7,11) (N(K1),K1=1,7)
      WRITE(7,12) (N(K1),K1=8,11)
      WRITE(7,14)
   14 FORMAT(80(' '))
      STOP
      END
```

```
&CONTROL OFF  NOMSG
GLOBAL TXTLIB FORTMOD2 MOD2EEH MOD2NFEH CMSLIB
&IF &3 = P &GOTO -A
&IF &3 = T &GOTO -B
-C
FILEDEF FT05F001 DISK &1 &2
LOAD SOLN
START
FILEDEF FT05F001 DISK &3 &4
LOAD SOLN
START
FILEDEF FT05F001 DISK &5 &6
LOAD SOLN
START
FILEDEF FT05F001 DISK &7 &8
LOAD SOLN
START
&EXIT
-A
FILEDEF FT06F001 PRINTER
&GOTO -C
-B
FILEDEF FT06F001 TERM
&GOTO -C
```

```
6.57E-4,8.55E-4,2.10E-3,2.50E-3,2.31E-6,1.04E-6,2.5E-6,0.5E-6
865,725,900,1120,25,1.05E7,5E6,.17,11
```

APPENDIX C

PREFORM/FIBER FABRICATION DATA

Table C-1. Preform/Fiber Fabrication Data.

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 20558	WG®-2	CE	790131-3	50	No	Too short
ES 20598	Vycor®	CE	-	-	-	Very weak
ES 20609	WG®-2	-	-	-	-	Shattered
ES 20742A	WG®-2	CE+OD (Si)	790531-2	305	Yes	
ES 20742B	WG®-2	GR+OD (Si)	790531-3	410	Yes	
ES 20746	WG®-2	GR+OD (Si)	790615-6	288	Yes	
ES 20749	WG®-2	GR+OD (Si)	790628-5	110	Yes	
ES 20756A	WG®-2	GR+FP+OD (Si)	790607-3	457	Yes	
ES 20756B	WG®-2	GR+OD (Si)	790613-5	400	Yes	
ES 20763	Vycor®	OD	790618-8	1635	Yes	Four-layer
ES 20768	Vycor®	-	-	-	-	Shattered
ES 20772	WG®-2	-	-	-	-	Shattered
ES 20776	WG®-2	GR+OD	790827-2	149	Yes	
ES 20778	SS®-2	-	-	-	-	Shattered

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 20781	Vycor®	OD	790628-2	1194	Yes	Four layer
ES 20787E	WG®-2	CE+OD (Ti)	790927-6	232	Yes	
ES 20831	Vycor®	-	-	-	-	Shattered
ES 20833	SS®-2	CE+OD (Si)	790927-7	69	Yes	
ES 20844	WG®-2	GR+OD (Si)	790828-7	305	Yes	
ES 20860	WG®-2	-	-	-	-	Shattered
ES 20871	WG®-2	GR	791010-5	536	Yes	
ES 20914	Vycor®	CE+OD (Si)	791009-2	867	Yes	
ES 40226	TO®-8	CE	790313-2	878	Yes	
ES 40228	WG®-2	CE	790316-3	25	No	Too short
ES 40232	WG®-2	-	-	-	-	CVD experiment
ES 40240	WG®-2	CE+OD (Si)	790529-4	137	Yes	
ES 40286	Vycor®	-	-	-	-	Incomplete preform

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40234	Vycor®	-	-	-	-	Shattered
ES 40238	Vycor®	-	-	-	-	Shattered
ES 40243	WG®-2	CE+OD (Si)	790329-1	400	Yes	
ES 40249	Vycor®	-	-	-	-	Contains large bubbles
ES 40250	Vycor®	-	-	-	-	Shattered
ES 40251	Vycor®	CE+OD (Si)	790515-1	20	Yes	Static fatigue test only
ES 40287	Vycor®	Flame Milling	-	-	-	Exp run
ES 40296	Vycor®	-	-	-	-	Shattered
ES 40298	Vycor®	OD (Si)	790607-6	673	Yes	Four layer
ES 40299	Vycor®	-	-	-	-	Shattered
ES 40301E	Vycor®	CE	790725-2	82	Yes	
ES 40303	Vycor®	-	-	-	-	Deformation

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40304	Vycor®	-	-	-	-	Failed
ES 40305	Vycor®	-	-	-	-	Shattered
ES 40307	Vycor®	-	-	-	-	Deformation
ES 40309	Vycor®	-	-	-	-	CVD system problem
ES 40311	Vycor®	-	-	-	-	Deformation
ES 40312	Vycor®	CE	-	-	-	Not drawn
ES 40315	Vycor®	-	-	-	-	Failed
ES 40319	Vycor®	-	-	-	-	Failed
ES 40326	Vycor®	CE+OD (Si)	790530-4	20	Yes	Static fatigue test only
ES 40329	Vycor®	CE	-	-	-	Nonuniform dimension
ES 40332	WG®-2	GR+FP+OD (Si)	790607-4	450	Yes	
ES 40334	WG®-2	-	-	-	-	Lathe problem

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40336	WG®-2	-	-	-	-	Deformation
ES 40338	WG®-2	-	-	-	-	Failed
ES 40346	WG®-2	GR+OD	-	-	-	Shattered
ES 40349	WG®-2	-	-	-	-	H_2 gas problem
ES 40353	SS®-2	CE	-	-	-	Pitting problem
ES 40354	WG®-2	-	-	-	-	Failed
ES 40359	WG®-2	-	-	-	-	Distorted preform
ES 40362	Vycor®	-	-	-	-	Shattered
ES 40363	WG®-2	GR+OD (Si)	790829-4	220	Yes	
ES 40365	Vycor®	-	-	-	-	Large bubbles
ES 40371E	WG®-2	CE+OD (Si)	790828-4	108	Yes	
ES 40371G	WG®-2	GR+OD (Si)	790828-9	320	Yes	
ES 40383	WG®-2	GR+OD (Si)	790927-4	858	Yes	

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40386	SS®-2	-	-	-	-	Not complete
ES 40399	WG®-2	-	-	-	-	Exhaust problem
ES 40400	WG®-2	-	-	-	-	Shattered
ES 40403	WG®-2	-	-	-	-	Failed
ES 40405	WG®-2	-	-	-	-	Failed
ES 40407	WG®-2	-	-	-	-	Bubble formation
ES 40408	WG®-2	-	-	-	-	Failed (lathe problem)
ES 40418	WG®-2	GR+FP+OD (Si)	791010-6	174	Yes	
ES 40426	WG®-2	-	-	-	-	Shattered
ES 40427	WG®-2	GR+OD (Si)	791010-8	434	Yes	
ES 40433	TO®-8	-	-	-	-	Shattered
ES 40434	TO®-8	-	-	-	-	Shattered

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40436	Vycor®	-	-	-	-	Shattered
ES 40437	Vycor®	CE	-	-	-	Cladding only
ES 40438	Vycor®	-	-	-	-	Shattered
ES 40439	Vycor®	CE+OD	-	-	-	Warpage problem
ES 40440	Vycor®	-	-	-	-	Shattered
ES 40448	TO®-8	GR+OD (Si)	791029-6	223	Yes	
ES 40460	WG®-2	GR+OD (Si)	791106-5	615	Yes	
ES 40461	Vycor®	GR+OD (Ti)	791106-6	182	No	Poor diameter control, Ti-doping exp
ES 40477	Vycor®	CE	-	-	-	Pitting problem
ES 40478	Vycor®	CE	-	-	-	Bubble problem

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40479	Vycor®	-	-	-	-	Failed
ES 40463	WG®-2	-	-	-	-	Failed
ES 40464	Vycor®	CE (Ti barrier)	791029-7	150	Yes	
ES 40465	Vycor®	-	-	-	-	Failed
ES 40470	Vycor®/ TO®-8	-	-	-	-	Exp run for CE
ES 40471	Vycor®/ TO®-8	-	-	-	-	Exp run for CE
ES 40481	Vycor®	-	-	-	-	Failed
ES 40482	Vycor®	-	-	-	-	Failed
ES 40483	Vycor®	CE	-	-	-	Shattered
ES 40484	Vycor®	-	-	-	-	Failed
ES 40487	Vycor®	CE (Ti barrier)	800327-2	184	Yes	
ES 40488	Vycor®	-	-	-	-	Failed
ES 40489B	Vycor®	CE (Ti barrier)	800123-1	106	Yes	Static fatigue and borosilicate

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40489I	Vycor®	CE (Ti barrier)	800130-2	119	Yes	Static fatigue (SF) and borosilicate
ES 40490	Vycor®	-	-	-	-	Failed
ES 40492A	Vycor®	CE (Ti barrier)	800123-2	125	Yes	High GE-doped cladding layer
ES 40493	Vycor®	-	-	-	-	Failed
ES 40494	Vycor®	-	-	-	-	Failed
ES 40495	Vycor®	-	-	-	-	Failed
ES 40496	Vycor®	CE (Ti barrier)	800327-7	35	Yes	SF test only
ES 40497	Vycor®	-	-	-	-	Failed
ES 40498I	Vycor®	CE (Ti barrier)	800130-3	160	Yes	
ES 40499	Vycor®	-	-	-	-	Pitting problem
ES 40500II	Vycor®	CE (Ti barrier)	800327-6	63	Yes	Very weak
ES 40502	Vycor®	-	-	-	-	Failed
ES 40509	Vycor®	-	-	-	-	Failed

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40513	Vycor®	-	-	-	-	Si_3N_4 barrier layer experiment
ES 40515	Vycor®	-	-	-	-	Failed
ES 40518	Vycor®	CE+OD	800206-5	252	Yes	
ES 40522	Pyrex®	-	-	-	-	Warpage problem
ES 40533	WG®-2	CE	-	-	-	Pitting Problem
ES 40536	WG®-2	-	-	-	-	Failed due to high P-dopant
ES 40538	WG®-2	-	-	-	-	Failed due to high P-dopant
ES 40542	WG®-2	-	-	-	-	Failed due to high P-dopant
ES 40543	WG®-2	-	-	-	-	Failed due to high P-dopant
ES 40546	WG®-2	-	-	-	-	Failed due to high P-dopant
ES 40548	WG®-2	-	-	-	-	Failed due to high P-dopant

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40551	WG®-2	-	-	-	-	Failed due to high P-dopant
ES 40553	WG®-2	-	-	-	-	Failed due to high P-dopant
ES 40556	WG®-2	-	-	-	-	Failed due to high P-dopant
ES 40558	WG®-2	-	-	-	-	Failed due to high P-dopant
ES 40560	WG®-2	CE	-	-	-	Shattered
ES 40565	WG®-2	-	-	-	-	Deformation
ES 40568	WG®-2	-	-	-	-	Failed
ES 40574	WG®-2	-	-	-	-	Failed
ES 40584	WG®-2	CE+OD (Ti)	800422-10	78	Yes	Bend test only
ES 40603	WG®-2	CE	-	-	-	Shattered
ES 40606	WG®-2	-	-	-	-	Large bubbles
ES 40475	Vycor®	CE (Ti barrier)	791106-4	1476	Yes	Ti-doping exp
ES 40605	WG®-2	-	-	-	-	Failed

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40609	WG®-2	-	-	-	-	Failed
ES 40611	WG®-2	-	-	-	-	Failed
ES 40614	WG®-2	CE	-	-	-	Shattered
ES 40616	WG®-2	OD (Ti)	800422-8	-	-	Too weak
ES 40619	WG®-2	-	-	-	-	Failed
ES 40639	WG®-2	CE	-	-	-	Shattered
ES 40642	WG®-2	-	-	-	-	Failed
ES 40650	WG®-2	CE (Ti barrier)	NDY*	-	-	
ES 40656A	WG®-2	CE (Ti barrier)	800422-6	20	Yes	Bend test only
ES 40657	WG®-2	CE	-	-	-	Shattered
ES 40661	WG®-2	CE (Ti barrier)	NDY*	-	-	
ES 40664A	WG®-2	CE (Ti barrier)	NDY*	-	-	
ES 40665	WG®-2	CE (Ti barrier)	NDY*	-	-	
ES 40668	WG®-2	-	-	-	-	Failed
ES 40670	WG®-2	-	-	-	-	Shattered

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

*Not Drawn Yet

Table C-1. Preform/Fiber Fabrication Data (continued).

Preform No	Substrate	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40688	WG®-2	-	-	-	-	Shattered
ES 40702	WG®-2	CE	-	-	-	Shattered
ES 40706	WG®-2	CE*	-	-	-	
ES 40710	WG®-2	CE*	-	-	-	Shattered
ES 40714	WG®-2	CE*	-	-	-	
ES 40716	WG®-2	CE*	-	-	-	
ES 40717	WG®-2	-	-	-	-	Deliverable preform
ES 40720	WG®-2	CE*	-	-	-	
ES 40722	WG®-2	-	-	-	-	Shattered
ES 40733	WG®-2	CE*	-	-	-	
ES 40735	WG®-2	CE*	-	-	-	
ES 40736	WG®-2	CE*	-	-	-	
ES 40747	WG®-2	CE*	-	-	-	
ES 40756	WG®-2	CE*	-	-	-	
ES 40757	WG®-2	CE*				

CE = Chemical Etching
Si = Silica
Ti = Ti-doped Silica

GR = Grinding
FP = Fire Polishing
OD = Outside Deposition

*Under Chem Etching

Table C-2. Graded Index Preform/Fiber Fabrication Data.

Preform No	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
EG 20774	None	790679-3	502	Yes	-
EG 20774A	GR+OD	790718-9	143	Yes	Nonuniform layer
EG 20774B	GR+FP	790621-7	390	Yes	-
EG 20803	None	790710-5	710	Yes	-
EG 20803A	GR+OD	790718-3	255	Yes	-
EG 20803B	GR	790723-2	245	Yes	-
EG 20819A	NA	790719-6	510	Yes	ECOM project fiber
EG 20819B	NA	790719-2	516	Yes	ECOM project fiber
EG 20819C	NA	790720-2	525	Yes	ECOM project fiber
EG 20819D	NA	790720-3	522	Yes	ECOM project fiber
EG 20842A	NA	790820-40	953	Yes	Furnace draw (case)
EG 20842B	NA	790820-5a	783	Yes	Flame draw (case)
EG 20847A	NA	790823-4	707	Yes	Case project fiber
EG 20847B	NA	790823-6	700	Yes	Case project fiber
EG 20847C	NA	790823-7	1150	Yes	Case project fiber
PG 30236	CE+OD	-	-	Yes	Production fiber
EG 30310	CE+OD (Ti)	800422-9	122	Yes	-
PG 30527I	CE+OD	800228-4	204	Yes	Production preform
PG 30527II	CE+OD	800327-4	179	Yes	Production preform

Legends: OD = Outside Deposition
GR = Center Grinding
FP = Fire Polishing
CE = Chemical Etching

Si = Silica Layer
Ti = Ti-Doped Silica Layer
SF = Static Fatigue

Table C-2. Graded Index Preform/Fiber Fabrication Data (continued).

Preform No	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
EG 40372A	None	790710-4	732	Yes	-
EG 40372B	CE+OD (Si)	790724-7	635	Yes	-
EG 40372E	CE+OD (Si)	790828-3	108	Yes	-
EG 40372G	GR+OD (Si)	790828-4	145	Yes	-
EG 40389A	None	790829-8	1620	Yes	-
EG 40389B	FP	790829-6	578	Yes	-
EG 40441A	None	791015-6	1506	No	-
EG 40441B	GR	791029-5	200	Yes	-
EG 40441C	GR+FP	791022-4	420	Yes	-
EG 40442	-	-	-	No	Failed
EG 40456	GR	791129-4	415	Dynamic test only	
EG 60028II	CE+OD (Si)	800411-8	50	No	Production preforms very weak
EG 60028IIa	CE+OD (Si)	800327-3	193	Yes	
LG 11204	None	791203-5a	-	SF test only	Large core fiber
HG 11046	None	-	-	SF test only	Large core fiber

Legends: OD = Outside Deposition
GR = Center Grinding
FP = Fire Polishing
CE = Chemical Etching
Si = Silica Layer
Ti = Ti-Doped Silica Layer
SF = Static Fatigue

Table C-3. Silica Rod Preform/Fiber Fabrication Data.

Preform No	Treatment	Fiber Id No	Drawn Length (m)	Test Done	Remarks
ES 40394	OD (Si)	790904-2	1190	Yes	SS®-2 rod
ES 40395	None	790831-3	912	Yes	SS®-2 rod
ES 40409	GR+FP	790914-4	448	Yes	SS®-2 rod
ES 40410	GR+FP+OD (Si)	790917-4	622	Yes	SS®-2 rod
ES 40411	OD (Si)	790917-6	930	Yes	SS®-2 rod
ES 40428A	None	790925-5	638	Yes	SS®-2 rod
ES 40428B	GR+FP+OD (Si)	791012-5	1011	Yes	SS®-2 rod
ES 40428C	CE+FP+OD (Si)	791005-4	563	Yes	SS®-2 rod
ES 40428D	CE+FP+OD (Ti)	791008-2	468	Yes	SS®-2 rod

Legends: OD = Outside Deposition
GR = Center Grinding
FP = Fire Polishing
CE = Chemical Etching
Si = Silica Layer
Ti = Ti-Doped Silica Layer

APPENDIX D

DATA PROCESSING PROGRAMS

D-1.0 DATA PROCESSING COMPUTER OPERATION

The following is an illustration of a typical data processing computer operation. This particular example displays the process of raw static fatique data.

```
data

  -If at any time during the operation of this program you want to
    leave simply type "OFF" and the hit the "ENTER" key.
    If at any time while in a section you want to restart that
    section simply type "R" or "RESTART" and hit the "ENTER" key.

  -Is the data in a file?
   (Answere Yes or No)
y

  -What is the name and filetype of your data file?
static data

  -Lets take one last look at the data.

   PLEASE MAKE SURE THE FOLLOWING CONTITIONS ARE MET:
        1) No negative or zero data entered
        2) If you wish to include zero values of enter a small value
           but not zero in its place.
        3) Enter no more than 100 points.
        4) There is one and only one comma between data values.

 -To get out of the EDGAR mode (and have this program continue running)
        1) Hit ENTER
        2) Type the word "FILE"
        3) Hit ENTER


   HIT ENTER WHEN READY

(enter)

ES-040489B       *
 800123-1
STF1
STANDARD STATIC FATIQUE TEST (EXAMPLE)
     445.0    4.90  20.8   72.0
     385.0    5.00  20.6   72.0
     410.0    4.90  20.4   72.0
     450.0    4.90  20.8   72.0
     390.0    5.00  20.8   72.0
    6000.0    5.10  21.2   83.0
  107520.0    5.00  20.0   83.0
     600.0    5.90  20.6   83.0
   40440.0    4.90  19.8   83.0
    6120.0    5.30  20.4   83.0
  593460.0    5.10  20.8   95.0
  402600.0    4.70  20.2   95.0
  239640.0    5.30  20.8   95.0
  163200.0    5.50  21.4   95.0

file
```

FILE: TERM1 FILE A ITT ELECTRO-OPTICAL PRODUCTS DIVISION

STATIC TEST DATA
STANDARD STATIC FATIQUE TEST (EXAMPLE)

FD (MIL)	OD (MIL)	MD (MIL)	STRESS (G PASCAL)	TIME TO FAILURE (SEC)
4.90	20.8	72.0	3.8017	445.
5.00	20.6	72.0	3.8877	385.
4.90	20.4	72.0	3.8182	410.
4.90	20.8	72.0	3.8017	450.
5.00	20.8	72.0	3.8793	390.
5.10	21.2	83.0	3.5240	6000.
5.00	20.0	83.0	3.4951	107520.
5.90	20.6	83.0	4.1004	600.
4.90	19.8	83.0	3.4319	40440.
5.30	20.4	83.0	3.6905	6120.
5.10	20.8	95.0	3.1710	593460.
4.70	20.2	95.0	2.9375	402600.
5.30	20.8	95.0	3.2953	239640.
5.50	21.4	95.0	3.4021	163200.

-Do you want furter data reduction?
Y

PREFORM NO. ES-040489B FIBER NO. 800123-1
STATIC TEST DATA
STANDARD STATIC FATIQUE TEST (EXAMPLE)

		COEFFICIENT OF DETERMINATION
LINEAR	T = .1778E+07 + -.4645E+06 S	0.664
EXPONENTIAL	T = .1457E+18 EXP (-8.491 S)	0.848
LOGARITHMIC	T = .2216E+07 + -.1652E+07 LN S	0.685
LOG-LOG	LOG T = -29.58 S + 20.29	0.839

USING LOG-LOG EQUATION

STRESS AT TIME TO FAILURE OF 10,000 SEC. = 3.5555 GIGA PASCAL
STRESS AT TIME TO FAILURE OF 1,000 SEC. = 3.8434 GIGA PASCAL

N VALUE = 29.5776

```
  -Do you want that sent to the printer?
y

  -Please enter name of the person to get or receive all
            the printed material
final

  -Do you want a plot of that data?
y

  -Do you have more data to enter?
n


0001 FILE  CHANGED
-There are 1 sets of multiple plots awaiting output


R;

msg op please attach plotter tape....thank you...pete
R;

TAPE 181 ATTACHED
08:23:49   MSG FROM OPER    :  TAPE IS READY

move
R;

tape run
R;

msg op thank you....
R;
```

The following are the computer source listings used in the previous example. The listings include:

- DATA EXEC - An executive that interacts between the laboratory technician and the various load modules and data files
- DATA FORTRAN - A FORTRAN source listing of the program used in processing the data
- STATIC DATA - An example of a typical static fatique raw date file

```
&CONTROL OFF NOMSG
*
*
*  GENERAL PURPOSE EXECUTIVE FOR CALCULATION, PRINTING AND PLOTTING
*    CALCULATED RESULTS.....P.H. PRIDEAUX APRIL 22, 1980
*                         UPDATED MAY 22, 1980
*
*
GLOBAL TXTLIB FORTMOD2 MOD2EEH MOD2NEEH CMSLIB
*  EXEC FORTH DATA
ERASE DATA PLOT
&P = 0
&O = 0
-DATA1
FILE FT01F001 DISK CCPLOT FILE (LRECL 80 BLOCK 800 PERM RECFM FB
FILE FT02F001 DISK PLOT DATA (LRECL 80 BLOCK 800 PERM RECFM FB
FILE FT03F001 DISK DEBUG TEMP (LRECL 132 BLOCK 792 PERM RECFM FB
FILE FT07F001 DISK DATA1 DATA (LRECL 132 BLOCK 792 PERM RECFM FB
FILE FT08F001 DISK DATA2 DATA (LRECL 132 BLOCK 792 PERM RECFM FB
&V = 1
CLEAR
&BEGTYPE

  -If at any time during the operation of this program you want to
    leave simply type "OFF" and the hit the "ENTER" key.
    If at any time while in a section you want to restart that
    section simply type "R" or "RESTART" and hit the "ENTER" key.
&END
&BEGTYPE

  -Is the data in a file?
&END
-DATA4
&BEGTYPE
   (Answere Yes or No)

&END
&READ VARS &1
&R = &1
&IF .&R = .  &GOTO -DATA4
&IF &R = RESTART  &GOTO -DATA1
&IF &R = R   &GOTO -DATA1
&IF &R = NO  &GOTO -ERASE
&IF &R = N   &GOTO -ERASE
&IF &R = YES &GOTO -FILE
&IF &R = Y   &GOTO -FILE
&IF &R = OFF &GOTO -EXIT
&GOTO -DATA4
-ERASE
CLEAR
ERASE DATA DATA
&BEGTYPE
   After you get done with this page you will be put into the edit mode
   of a new file. First enter the Preform ID Number on the first line
   then the Fiber ID number on the second line. The type of data in the
```

```
   file 'DYN1' for standard dynamic data, 'BND1' for bending dynamic
   data 'STF1' for standard static fatique data in the next line. In the
   forth line type in remarks. Follow this with the data.

&END
&BEGTYPE
ES-040489B                          (preform number...first 12 characters)
 800123-1                           (fiber number....first 12 characters)
STF1                                (data type  STF1, DYN1, or BND1)
STANDARD STATIC FATIQUE TEST        (remarks...first 40 chracters)
     445    4.90   20.8    72.0
     385    5.00   20.6    72.0
     410    4.90   20.4    72.0
     450    4.90   20.8    72.0        (data...as described below)
     390    5.00   20.8    72.0

 -for static fatique results enter in this order
    time to failure... fiber diameter... coating diameter..
    and mandrel diameter. (all units to be in mils)

 -for dynamic strength results enter
    total load on fiber... and fiber diameter.

 -for bending test results enter
    micrometer reading... coating diameter... and fiber diameter

&END
-ERASE1
&A = DATA
&B = DATA
&GOTO -EDIT1
-FILE
&BEGTYPE
 -What is the name and filetype of your data file?

&END
&READ VARS &1 &2
&A = &1
&B = &2
&IF .&A = .  &GOTO -FILE
&IF &A = OFF &GOTO -EXIT
&IF &A = R   &GOTO -DATA1
&IF &A = RESTART  &GOTO -DATA1
&IF .&B = .  &GOTO -FILE
-EDIT2
&V = 2
&BEGTYPE
 -Lets take one last look at the data.

&END
-EDIT1
FILE FT04F001 DISK &A &B
&BEGTYPE

   PLEASE MAKE SURE THE FOLLOWING CONTITIONS ARE MET:
```

```
        1) No negative or zero data entered
        2) If you wish to include zero values of enter a small value
           but not zero in its place.
        3) Enter no more than 100 points.
        4) There is one and only one comma between data values.

 -To get out of the EDGAR mode (and have this program continue running)
        1) Hit ENTER
        2) Type the word "FILE"
        3) Hit ENTER

&END
-LOOP1
&BEGTYPE

   HIT ENTER WHEN READY

&END
&READ VARS &1
&R = &1
&IF .&R = .  &GOTO -EDIT3
&IF &R = OFF &GOTO -EXIT
&IF &R = R   &GOTO -DATA1
&IF &R = RESTART &GOTO -DATA1
&GOTO -LOOP1
-EDIT3
EDGAR &A &B A
&IF &V = 1 &GOTO -EDIT2
CLEAR
FILE FT04F001 DISK &A &B A (LRECL 80 BLOCK 800 PERM RECFM FB
* LOAD DATA
* GENMOD DATA
* START
DATA
TYPE DATA1 DATA
-LOOP2
&BEGTYPE

  -Do you want furter data reduction?

&END
&READ VARS &1
&R = &1
&IF .&R = .  &GOTO -LOOP2
&IF &R = NC  &GOTO -LOOP3
&IF &R = N   &GOTO -LOOP3
&IF &R = YES &GOTO -CURVE
&IF &R = Y   &GOTO -CURVE
&IF &R = OFF &GOTO -EXIT
&IF &R = R   &GOTO -DATA1
&IF &R = RESTART &GOTO -DATA1
&GOTO -LOOP2
-CURVE
CLEAR
```

```
TYPE DATA2 DATA
-LOOP3
&BEGTYPE

  -Do you want that sent to the printer?

&END
&READ VARS &1
CLEAR
&R = &1
&IF .&R = .  &GOTO -LOOP3
&IF &R = OFF &GOTO -EXIT
&IF &R = Y   &GOTO -PRINT1
&IF &R = YES &GOTO -PRINT1
&IF &R = NO  &GOTO -LOOP4
&IF &R = N   &GOTO -LOOP4
&IF &R = R   &GOTO -DATA1
&IF &R = RESTART &GOTO -DATA1
&GOTO -LOOP3
-PRINT1
&IF &C NE 0  &GOTO -PRINT3
&O = 1
CP SET MSG OFF
-PRINT2
&BEGTYPE

  -Please enter name of the person to get or receive all
                the printed material

&END
&READ VARS &1
&D = &1
&IF .&D = .  &GOTO -PRINT2
&IF &D = OFF &GOTO -EXIT
&IF &D = R   &GOTO -DATA1
&IF &D = RESTART &GOTO -DATA1
-PRINT3
CP SPOOL PRINTER CONT HOLD
PRINT DATA1 DATA
CP SPOOL PRINTER NOCONT HOLD
PRINT DATA2 DATA
ERASE DATA1 DATA
ERASE DATA2 DATA
-LOOP4
&BEGTYPE

  -Do you want a plot of that data?

&END
&READ VARS &1
&R = &1
&IF .&R = .  &GOTO -LOOP4
&IF &R = OFF &GOTO -EXIT
&IF &R = Y   &GOTO -PLOT
&IF &R = YES &GOTO -PLOT
```

```
&IF &R = NO  &GOTO -LOOP5
&IF &R = N   &GOTO -LOOP5
&IF &R = R   &GOTO -DATA1
&IF &R = RESTART &GOTO -DATA1
&GOTO -LOOP4
-PLOT
&P = &P + 1
FILE FT05F001 DISK JUNK5 TEMP (LRECL 80 BLOCK 800 PERM RECFM FB
FILE OUTBUF DISK DATA PLOT (DISP MOD LRECL 508 BLOCK 508 RECFM F
PLOT15
FILE INMOVE DISK DATA PLOT (LRECL 508 BLOCK 508 PERM RECFM F
FILE OUTMOVE TAP1 (LRECL 508 BLOCK 508 PERM RECFM F
-LOOP5
&BEGTYPE

  -Do you have more data to enter?

&END
&READ VARS &1
&R = &1
&IF .&R = .  &GOTO -LOOP5
&IF &R = YES &GOTO -DATA1
&IF &R = Y   &GOTO -DATA1
&IF &R = NO  &GOTO -EXIT
&IF &R = N   &GOTO -EXIT
&IF &R = OFF &GOTO -EXIT
&IF &R = R   &GOTO -DATA1
&IF &R = RESTART &GOTO -DATA1
&GOTO -LOOP5
-EXIT
&IF &O = 0 &GOTO -EXIT2
CP CHANGE PRINTER ALL DIST &D NOHOLD
-EXIT2
&IF &P NE 0 &TYPE  -There are &P sets of multiple plots awaiting output
ERASE PLOT DATA
CP SET MSG ON
&EXIT
&CONTROL ALL
```

```
C
C
C PROGRAM NAME- DATA (TEST CALCULATIONS-DYNAMIC, BENDING, STATIC)
C       WRITTEN BY P.H. PRIDEAUX     MAY  6, 1980
C                MODIFIED  MAY 22, 1980
C
C
C VARIABLES.....
C
C
C COAT -COATING DIAMETER
C DIAM -MANDREL DIAMETER
C F( , ) -DATA DISPLAY VARIABLE... '*****' INDICATES THAT THIS DATA WAS
C  SELECTED AND USED IN THE DETERMINATION OF EQUATION CONSTANTS AND
C  WAS WITHIN 2 STD OF THE RESULTING EQUATION. '**   ' INDICATES THAT
C  THIS DATA WAS SELECTED IN THE DETERMINATION OF THE EQUATION CONSTANTS
C  BUT WAS NOT WITHIN 2 STD OF THE EQUATION. '   **' INDICATES THAT THIS
C  DATA WAS NOT SELECTED BUT WAS WITHIN 2 STD OF THE RESULTING EQUATION.
C  '     ' INDICATES THAT THIS DATA WAS NOT SELECTED AND WAS NOT WITHIN
C  2 STD OF THE GENERATED EQUATION.
C FIBER( ) -PREFORM ID NUMBER STORED HERE
C FIBR -FIBER DIAMETER
C KIND -KIND=1 STATIC FATIQUE; KIND=2 DYNAMIC; KIND=3 BENDING
C LSTRESS -LOG OF STRESS VALUE
C OD -OVERALL DIAMETER
C PREFRM( ) -PREFORM ID NUMBER STORED HERE
C TFAIL -TIME OF FAILURE
C TL -TOTAL LOAD AS READ FROM INDICATOR (POUNDS)
C S# -VARIOUS SUMMATIONS
C
C
C
      REAL INT,LTIME,LTRESS,LTRES2,LTIME2,M,MD,MEAN
      DIMENSION TIME(100),D(100),LTIME(100)
      DIMENSION PRODUC(100),LTRES2(100),LTIME2(100)
      DIMENSION NVL(5),NVU(5),STRESS(100),F(100,5),Y(100),LTRESS(100)
      DIMENSION STRES2(100),DATA(50),ALIN(5),BLIN(5),R2LIN(5)
      DIMENSION PREFRM(3),FIBER(3),STD(5),TYPE(3),PLOT(2,3),RE(10)
      DATA BLANK,AST,FHALF,SHALF/'     ','*****','**   ','   **'/
      DATA TYPE/'STF1','DYN1','BND1'/
      DATA PLOT/' STA','TIC ','STAN','DARD','BEND','ING '/
      READ (4,400,END=99) (PREFRM(I),I=1,3),(FIBER(J),J=1,3)
  400 FORMAT(3A4,/,3A4)
      WRITE (2,700) (PREFRM(J),J=1,3),(FIBER(K),K=1,3)
      READ (4,410,END=99) ANS
      KIND=0
      IF (ANS.EQ.TYPE(1)) KIND=1
      IF (ANS.EQ.TYPE(2)) KIND=2
      IF (ANS.EQ.TYPE(3)) KIND=3
      IF (KIND.EQ.0) GO TO 90
  410 FORMAT (1A4)
      READ (4,420,END=99) (RE(I),I=1,10)
  420 FORMAT (10A4)
      WRITE (7,700) (PREFRM(J),J=1,3),(FIBER(K),K=1,3)
      WRITE (8,700) (PREFRM(J),J=1,3),(FIBER(K),K=1,3)
```

```
  700 FORMAT (2X,'PREFORM NO. ',3A4,10X,'FIBER NO. ',3A4)
      WRITE (7,710) (PLOT(I,KIND),I=1,2),(RE(J),J=1,10)
      WRITE (8,710) (PLOT(I,KIND),I=1,2),(RE(J),J=1,10)
  710 FORMAT (16X,2A4,' TEST DATA',/,20X,10A4,/)
      NT=0
      GO TO (10,50,60), KIND
   10 WRITE (7,720)
  720 FORMAT (////,9X,'FD',7X,'OD',8X,'MD',12X,'STRESS',5X,'TIME TO FAIL
     CURE',/,8X,'(MIL)',4X,'(MIL)',5X,'(MIL)',9X,'(G PASCAL)',6X,'(SEC)
     C')
      K=0
      L=0
      S1=0
      S2=0
      S3=0
      S4=0
      S5=0
      S6=0
      S7=0
      S8=0
      S9=0
      S10=0
      S11=0
      S12=0
C
C READING IN THIS ORDER   TIME TO FAILURE, FIBER DIAMETER,
C   COATING DIAMETER AND MANDREL DIAMETER
C
      DO 26 I=1,100
      READ(4,*,ERR=92,END=28) TFAIL,FIBR,COAT,DIAM
      LTIME(I)=ALOG10(TFAIL)
C
C CALCULATING IN GIGA PASCALS
C
      STRESS(I)=((7.2E04*0.5*FIBR)/(0.5*(COAT+DIAM)))/1000.0
      LTRESS(I)=ALOG10(STRESS(I))
      WRITE (7,730) FIBR,COAT,DIAM,STRESS(I),TFAIL
  730 FORMAT (9X,F4.2,5X,F4.1,5X,F5.1,5X,5X,F6.4,8X,F7.0)
      WRITE (2,210)  LTRESS(I),LTIME(I),STRESS(I),TFAIL
  210 FORMAT (5X,E12.6,5X,E12.6,5X,E12.6,5X,E12.6)
C
C THESE EQUATIONS GENERATE THE SUMMATIONS OF THE VARIABLES FOR USE IN
C COMPUTING THE FOUR REGRESSIONS.
C
      S1 = S1 + STRESS(I)
      S2 = S2 + TFAIL
      S3 = S3 + STRESS(I)**2
      S4 = S4 + TFAIL**2
      S5 = S5 + STRESS(I)*TFAIL
      S12= S12+ (LOG(STRESS(I)))*LOG(TFAIL)
      IF (STRESS(I)) 20,20,12
   12 S7 = S7 + LOG(STRESS(I))
      S9 = S9 + TFAIL*LOG(STRESS(I))
      S10= S10+ (LOG(STRESS(I)))**2
   14 IF (TFAIL) 22,22,16
```

```
   16 S6 = S6 + LOG(TFAIL)
      S8 = S8 + STRESS(I)*LOG(TFAIL)
      S11= S11+ (LOG(TFAIL))**2
      GOTO 24
   20 K = 1
      GOTO 14
   22 L = 1
   24 NT=NT+1
   26 CONTINUE
   28 CONTINUE
C
C
C OK. HERE WE GO INTO THE CALCULATIONS OF THE CURVE FITTING CONSTANTS.
C
C LETS USE THE CONSTANTS ALIN, BLIN, R2LIN FOR THE LINEAR FIT.  LIKE-
C WISE LETS USE AEXP, BEXP, R2EXP, ALN, BLN, R2LN, APWR, BPWR AND
C R2PWY FOR THE CONSTANTS ASSOCIATED WITH EXPONENTIAL, NATURAL LOG AND
C POWER CURVE FITS.
C
   30 BLIN(1)=(S5-S1*S2/NT)/(S3-S1**2/NT)
      ALIN(1)=S2/NT-BLIN(1)*S1/NT
      R2LIN(1)=((S5-S1*S2/NT)**2)/((S3-S1**2/NT)*(S4-S2**2/NT))
C Y=A+BX
C
C
      IF (L) 31,31,32
   31 BEXP=(S8-S1*S6/NT)/(S3-S1**2/NT)
      AEXP=EXP(S6/NT-BEXP*S1/NT)
      R2EXP=((S8-S1*S6/NT)**2)/((S3-S1**2/NT)*(S11-S6**2/NT))
C Y= A EXP (BX)
C
C
   32 IF (K) 33,33,35
   33 BLN=(S9-S7*S2/NT)/(S10-S7**2/NT)
      ALN=S2/NT-BLN*S7/NT
      R2LN=((S9-S2*S7/NT)**2)/((S10-S7**2/NT)*(S4-S2**2/NT))
C Y= A+B LN(X)
C
C
      IF (L) 34,34,35
   34 BPWR=(S12-S7*S6/NT)/(S10-S7**2/NT)
      APWR=EXP(S6/NT-BPWR*S7/NT)
      R2PWR=((S12-S7*S6/NT)**2)/((S10-S7**2/NT)*(S11-S6**2/NT))
      ALPWR=ALOG10(APWR)
C Y=A X**B
C
C
   35 WRITE (8,810) ALIN(1), BLIN(1), R2LIN(1)
  810 FORMAT (59X,'COEFFICIENT',/,63X,'OF',/,58X,'DETERMINATION'//,
     C'LINEAR',12X,'T = ',G10.4,'  +  ',G10.4,'  S',13X,F6.3,//)
      IF (L) 36,36,37
   36 WRITE (8,820) AEXP, BEXP, R2EXP
  820 FORMAT ('EXPONENTIAL', 7X,'T = ',G10.4,' EXP ( ',G10.4,' S)',
     C11X,F6.3,//)
   37 IF (K) 38,38,99
```

```
   38 WRITE (8,830) ALN, BLN, R2LN
  830 FORMAT('LOGARITHMIC', 7X,'T = ',G10.4,' + ',G10.4,' LN S',
     C13X, F6.3,//)
      IF (L) 39,39,99
   39 WRITE (8,840) BPWR, ALPWR, R2PWR
  840 FORMAT ('LOG-LOG',7X,'LOG T = ',G10.4,' S +',2X,G10.4,
     C 15X,F6.3,//)
      TF3=(10.0**((3.0-ALPWR)/BPWR))
      TF4=(10.0**((4.0-ALPWR)/BPWR))
      VN=ABS(BPWR)
C
C  WRITING CONTROL FILE FOR PLOT15 (PHP'S GENERAL DATA PLOTTING ROUTINE)
C
      WRITE (8,850) TF4,TF3,VN
  850 FORMAT(//,'USING LOG-LOG EQUATION',//,
     C'STRESS AT TIME TO FAILURE OF 10,000 SEC. = ',F7.4,' GIGA PASCAL',
     C//,'STRESS AT TIME TO FAILURE OF  1,000 SEC. = ',F7.4,
     C' GIGA PASCAL',//,33X,'N VALUE = ',F7.4)
      WRITE(1,100) NT,(PREFRM(J),J=1,3),(FIBER(K),K=1,3)
  100 FORMAT('01,100142' ,/, ' 2 ',1I5,/,' 5.50 7.50',/,'LNLG',/,
     C'STRESS (G PASCAL)',/,'TIME TO FAILURE (SEC)',/,
     C'STATIC FATIQUE DATA',/,'PREFORM-',3A4,' FIBER-',3A4,/,
     C'1.42,8.0,0.2,7.65',/,'(39X,E12.6,5X,E12.6)')
      WRITE(1,110) NT,(PREFRM(J),J=1,3),(FIBER(K),K=1,3),TF4,TF3,VN
  110 FORMAT ('01,100146',/,' 2 ',1I5,/,' 5.50 7.50',/,'LGLG',/,
     C'STRESS (G PASCAL)',/,'TIME TO FAILURE (SEC)',/,
     C'STATIC FATIQUE DATA',/,'PREFORM-',3A4,' FIBER-',3A4,/,
     C'FAILURE STRESS AT',/,'10000 SEC=',F5.3,/,' 1000 SEC=',F5.3,/,
     C'N=',F5.1,/,'1.42,8.0,0.2,7.65,0.16,1.3,0.3,1.0,0.3,0.8,1.28,0.6'
     C,/,'(39X,E12.6,5X,E12.6)')
      GO TO 99
   50 WRITE (7,740)
  740 FORMAT (//,10X,'   LOAD   ',5X,' DIAMETER ',5X,'  STRESS  ',/,
     C 10X,'   (LBS)   ',5X,'  (MILS)   ',5X,' (G PASCAL)',/)
      DO 52 I=1,100
      READ(4,*,ERR=92,END=64) FORCE,FIBR
C
C CALCULATE STRESS FROM LOAD & DIAMETER
C
      FORCE=FORCE/2.0
      STRESS(I)=((14.0*FORCE)/(11.0*(FIBR**2)))*6.895
      LTRESS(I)=ALOG10(STRESS(I))
      WRITE (7,750) FORCE,FIBR,STRESS(I)
  750 FORMAT(13X,F5.2,9X,F5.2,9X,F6.3)
      F(I,1)=AST
      F(I,2)=AST
      F(I,3)=AST
      F(I,4)=AST
      F(I,5)=AST
      NT=NT+1
   52 CONTINUE
      GO TO 64
   60 WRITE (7,760)
  760 FORMAT (//,'      DIAL     BENDING    COATING     FIBER      ',
     C'STRESS',/,'      READING   DIAMETER   DIAMETER   DIAMETER    ',
```

```
     C'G PASCAL',/)
      DO 62 I=1,100
      READ(4,*,ERR=92,END=64) READ,COATD,FIBR
C
C CALCULATE STRESS FROM LOAD & DIAMETER
C
      RAD=READ-562.5
      STRESS(I)=((1.05E+04*FIBR)/(RAD-COATD))*0.006895
      LTRESS(I)=ALOG10(STRESS(I))
      WRITE (7,770) READ,RAD,CCATD,FIBR,STRESS(I)
  770 FORMAT(5X,F6.2,5X,F6.2,5X,F6.2,5X,F6.2,5X,F6.3)
      F(I,1)=AST
      F(I,2)=AST
      F(I,3)=AST
      F(I,4)=AST
      F(I,5)=AST
      NT=NT+1
   62 CONTINUE
   64 N=NT
C
C ARRANGE STRESS VALUES IN DECREASING ORDER
C
   65 M=0
      DO 66 I=2,NT
      IF (STRESS(I).LE.STRESS(I-1)) GO TO 66
      T=STRESS(I-1)
      STRESS(I-1)=STRESS(I)
      STRESS(I)=T
      R=LTRESS(I-1)
      LTRESS(I-1)=LTRESS(I)
      LTRESS(I)=R
      M=1
   66 CONTINUE
      IF (M.NE.0) GO TO 65
      JT=5
      IF (NT.LE.6) JT=1
      NVL(1)=1
      NVL(2)=1
      NVL(3)=1
      NVL(4)=NT/3
      NVL(5)=(NT*2)/3
      NVU(1)=NT
      NVU(2)=(NT*2)/3
      NVU(3)=NT/3
      NVU(4)=NT
      NVU(5)=NT
      Y(1)=(LOG(LOG(1/(0.0001))))
      DO 78 J=1,JT
      IF (NT.EQ.0) GO TO 78
      X=0
      K=0
      S1=0
      S2=0
      S3=0
      S4=0
```

```
      S5=0
      NV=1+NVU(J)-NVL(J)
      NVLO=NVL(J)
      NVUO=NVU(J)
      NL=NVLO
      ANT=(1.0/NV)
C
C ASSIGN PROBABILITY OF FAILURE GIVEN THE NO. OF DATA POINTS
C
      DO 68 I=2,NV
      Y(I)=(LOG(LOG(1/(((I-1)*ANT)))))
   68 CONTINUE
      DO 70 I=1,NV
      S1 = S1 + LTRESS(NL)
      S2 = S2 + Y(I)
      S3 = S3 + LTRESS(NL)**2
      S4 = S4 + Y(I)**2
      S5 = S5 + LTRESS(NL)*Y(I)
      NL=NL+1
   70 CONTINUE
C
C Y=A+B*LOG(X)
C
      BLIN(J)=(S5-(S1*S2/NV))/(S3-(S1**2/NV))
      ALIN(J)=(S2/NV)-(BLIN(J)*S1/NV)
      R2LIN(J)=((S5-(S1*S2/NV))**2)/((S3-(S1**2/NV))*(S4-(S2**2/NV)))
C
C STANDARD ERROR OF ESTIMATE
C
      NL=NVLO
      DO 74 I=1,NV
      X=X+((LTRESS(NL)-((Y(I)-ALIN(J))/BLIN(J)))**2)
      NL=NL+1
   74 CONTINUE
      IF (NV.EQ.2.0) GO TO 78
      STD(J)=SQRT(X/(NV-2))
      STAN=(2.0*(STD(J)))
      ANT=(1.0/NT)
      X=ABS(LTRESS(1)-((Y(1)-ALIN(J))/BLIN(J)))
      IF (X.LE.STAN) GO TO 75
      F(1,J)=FHALF
      IF (1.EQ.NVLO) GO TO 76
      F(1,J)=BLANK
      GO TC 76
   75 IF (1.EQ.NVLO) GO TO 76
      F(1,J)=SHALF
   76 DO 78 I=2,NT
      Y(I)=(LOG(LOG(1/(((I-1)*ANT)))))
      X=ABS(LTRESS(I)-((Y(I)-ALIN(J))/BLIN(J)))
      IF (X.LE.STAN) GO TO 77
      F(I,J)=FHALF
      IF (I.LE.NVUO.AND.I.GE.NVLO) GO TO 78
      F(I,J)=BLANK
      GO TC 78
   77 IF (I.LE.NVUO.AND.I.GE.NVLO) GO TO 78
```

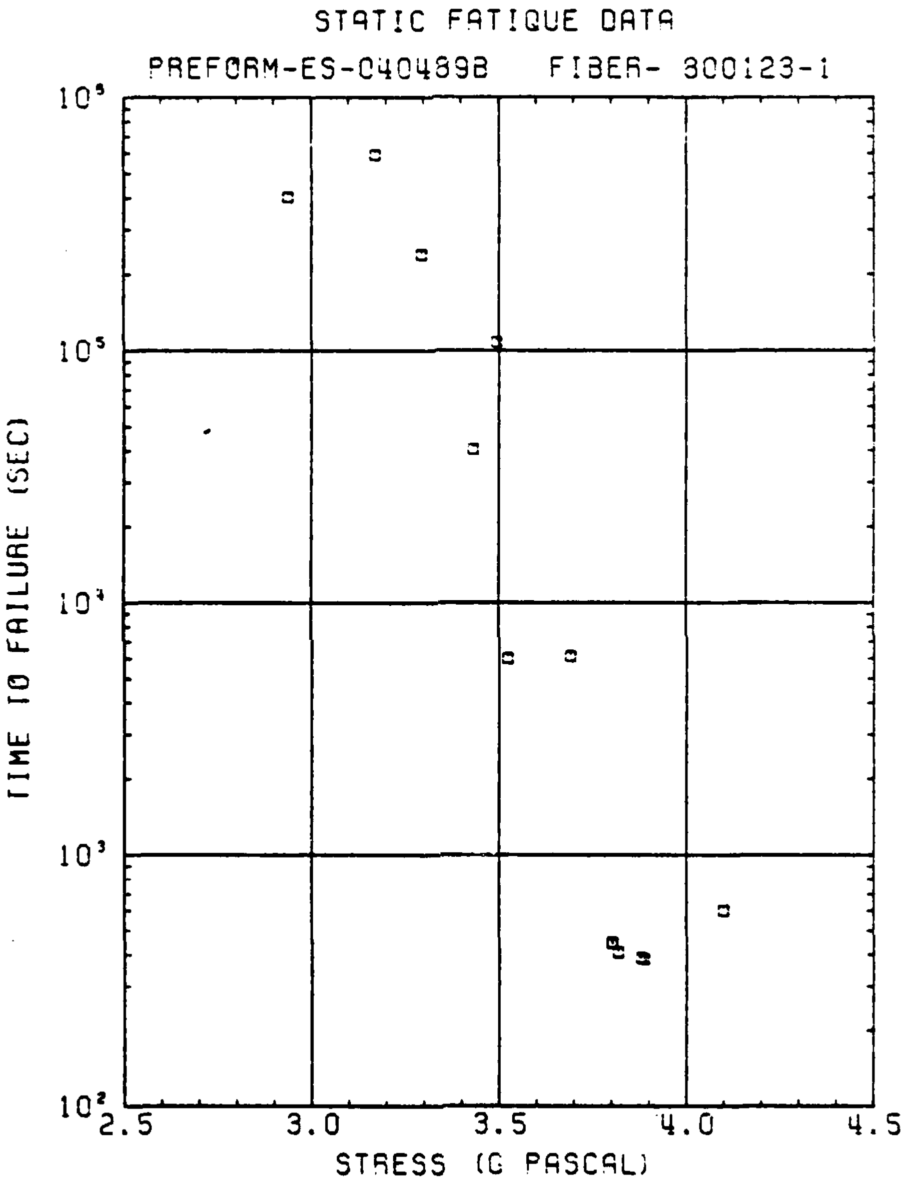
```
      F(I,J)=SHALF
   78 CONTINUE
      NT=N
C
C PRINT CALCULATED VALUES
C
      WRITE (8,890)  (ALIN(J),J=1,5),(BLIN(J),J=1,5),(R2LIN(J),J=1,5),
     C (STD(J),J=1,5)
  890 FORMAT ('LOG(LOG(1/(1-F))) = A + M*(LOG(STRESS))',//,4X,
     C 'INTERCEPT - A = ',5(E10.4,2X),/,8X,'SLOPE - M = ',5(E10.4,2X),
     C /,5X,'COEFF OF DET = ',5(E10.4,2X),/,
     C14X,'STD = ',5(E10.4,2X),//,
     C 12X,'STRESS       VALUES WITHIN 2.0 STD OF ABOVE EQUATION')
      A=0.0
      DO 80 I=1,NT
      WRITE (8,898) Y(I),STRESS(I),(F(I,J),J=1,5)
  898 FORMAT(1X,F7.3,3X,F7.3,4X,5(2X,1A4,6X))
      WRITE (2,220) STRESS(I),Y(I)
  220 FORMAT (2X,E12.6,2X,E12.6)
      A=A+STRESS(I)
   80 CONTINUE
      A=A/NT
      SX=STRESS(1)
      SN=STRESS(NT)
      NT=NT+1
C
C  WRITING CONTROL FILE FOR PLOT15 (PHP'S GENERAL DATA PLOTTING ROUTINE)
C
      WRITE(1,120)NT,(RE(I),I=1,10),(PLOT(J,KIND),J=1,2),
     C (PREFRM(K),K=1,3),(FIBER(L),L=1,3),SX,SN,A,BLIN(1)
  120 FORMAT('01,100147' ,/, ' 2 ',I15,/,' 5.50 7.50',/,'LGLN',/,
     C'STRESS  (G PASCAL)',/,'LOG(LOG(1/1-F))',/,10A4,/,
     C'DYNAMIC TEST DATA '2A4,/,'PREFORM-',3A4,' FIBER-',3A4,/,
     C 'MAX=',F7.3,' G PA',/,'MIN=',F7.3,' G PA',/,
     C 'AVG=',F7.3,' G PA',/,'  M=',F7.3,/,
     C'0.0,0.0,0.86,8.0,0.2,7.65,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0',/,
     C'(2X,E12.6,2X,E12.6)')
      GO TO 99
C
C  SIMPLE ERROR HANDLING ROUTINES
C
   90 WRITE (7,790)
      WRITE (8,790)
  790 FORMAT(//,'UNKNOWN TYPE OF DATA FILE TYPE ON LINE 3 OF DATA FILE',
     C/,'DATA TYPE MUST BE ''STF1'', ''DYN1'', OR ''BND1'' ')
      GO TO 99
   92 WRITE (7,792) NT
      WRITE (8,792) NT
  792 FORMAT (//,'IMPROPER DATA IN THE ',I13,' RECORD OF THE DATA FILE')
   99 STOP
      END
```

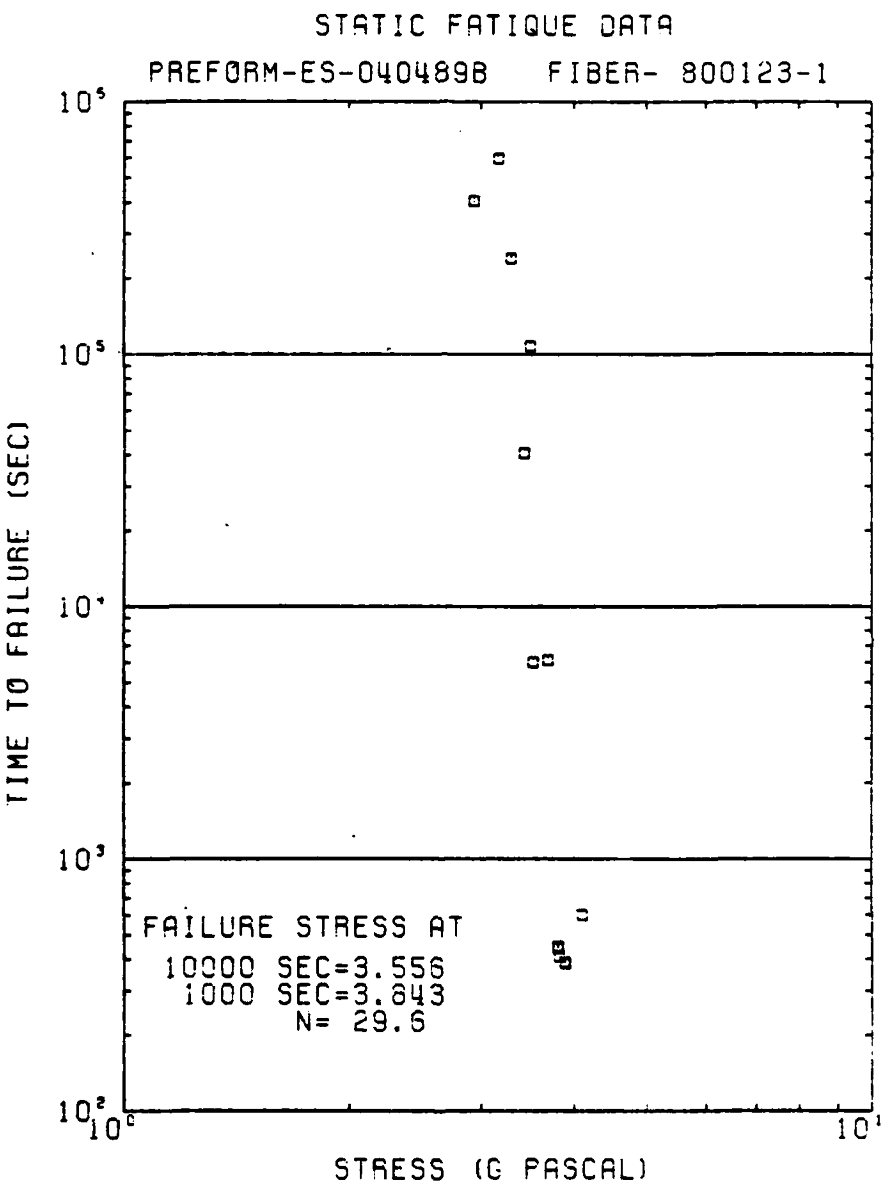
FILE: STATIC DATA A ITT ELECTRO-OPTICAL PRODUCTS DIVISION

ES-040489B *
800123-1
STF1
STANDARD STATIC FATIQUE TEST (EXAMPLE)

445.0	4.90	20.8	72.0
385.0	5.00	20.6	72.0
410.0	4.90	20.4	72.0
450.0	4.90	20.8	72.0
390.0	5.00	20.8	72.0
6000.0	5.10	21.2	83.0
107520.0	5.00	20.0	83.0
600.0	5.90	20.6	83.0
40440.0	4.90	19.8	83.0
6120.0	5.30	20.4	83.0
593460.0	5.10	20.8	95.0
402600.0	4.70	20.2	95.0
239640.0	5.30	20.8	95.0
163200.0	5.50	21.4	95.0

The following are the plots that result from the running of the previously illustrated data processing program.


STATIC FATIQUE DATA
PREFORM-ES-0404898   FIBER- 300123-1
TIME TO FAILURE (SEC)
STRESS (G PASCAL)
2.5
3.0
3.5
4.0
4.5
10²
10³
10⁴
10⁵



STATIC FATIQUE DATA
PREFORM-ES-040489B FIBER- 800123-1
TIME TO FAILURE (SEC)
STRESS (G PASCAL)
FAILURE STRESS AT
10000 SEC=3.556
1000 SEC=3.843
N= 29.6

APPENDIX E

HIGH STRENGTH, LONG LENGTH

OPTICAL FIBERS

PROCESS SPECIFICATION

1.0 SCOPE

The process to be defined is the fabrication of a high strength, long length optical fiber with a compressive cladding. This specification will document the fabrication process in sufficient detail in order that anyone with similar equipment and knowledge in the art of optical fiber fabrication can duplicate these techniques.

2.0. APPLICABLE DOCUMENTS

The Technical Proposal No R77-043 submitted by ITT Electro-Optical Products Division on November 1, 1977 and the Eighth Bimonthly Progress Report written under this contract (contract N00123-79-C-0301) are the only two documents referenced to in this text.

3.0 REQUIREMENTS

The following are the minimum requirements necessary to produce long length optical fiber with a highly compressed surface layer. The surface layer, which was produced under this contract, increases the durability of a fiber.

3.1 Equipment

3.1.1 Glass Cleaning Station

This station should be capable of properly handling hydrofluoric and nitric acids (liquid and fumes) which are present during glass cleaning. It should be of adequate area to enable the cleaning of approximately three foot silica tubes while providing a safe environment for the technician.

3.1.2 Glassworking Lathe

This lathe must be capable of supporting glass sizes of up to 37 mm in diameter. Support should consist of chucks on both head and tail stocks and these units must rotate up to 150 rpm while maintaining the set speed within ±2%. The fire carriage should be capable of traversing at least 70 cm between the head and tail stocks. The fire carriage must maintain a smooth traverse over a range of speeds from 1 to 20 cm/min within ±1% of the set value. A switching system must be present to change the fire carriage direction, while the return speed should be fast enough to prevent delays and damage to the preforms. A traverse delay at the intake and exhaust ends is also required. The delay should be capable of being varied up to 10 s depending upon process conditions. The fire carriage will be equipped with an oxyhydrogen torch which has an adjustable height as well as individual torch adjustments for the hydrogen and oxygen so that a proper deposition temperature can be attained. An optical pyrometer should be use to continuously monitor the deposition temperature throughout the process. Oxyhydrogen hand torches must be available at both head and tail stocks to aid in preform preparation.

3.1.3 Chemical Delivery System

This system will be used to deliver gaseous chemicals to the deposition torch and/or substrate tube on the glass fabrication lathe. The unit consists of a constant temperature enclosure capable of maintaining ±0.5°C while the delivery system is in use. Contained in this enclosure are the chemical bubbler for the $SiCl_4$, T_iCl_4, and $POCl_3$. The bubbler should be equipped to deliver a controlled flow of oxygen through the bubblers to the process line. Chemicals such as oxygen, helium, and BCl_3 are delivered through gas controllers and into the process lines. All gas flows must be controlled to ±2% of designated flow as specified in Tables 3-1, 3-2, and 3-3.

Each of these chemical vapors and gases is valved; this allows only the specific chemicals called for to be delivered to the process at any given time. The process line consists of a transfer line from the chemical delivery system to the glass-working lathe.

The process line is connected to either the deposition torch or to the intake end of the tube assembly via a rotary coupling and a filter.

This entire system should be free from leaks, not permeable to moisture, and free from metal impurities which will adversely affect the quality of the deposited glass. The system should be purged with dry nitrogen when not in use.

Table 3-1. Preform Fabrication Parameters for the Standard Three-Layered, Internally Deposited Compressive Cladded Fiber.

	Compressive Layers	Transition Layers	Cladding Layers	Core Layers
No of Passes	20	4	38	10
Deposition Temperature (°C)	1920	1920-1760	1760	1950
Oxygen Flows thru bubblers (sccm)				
$SiCl_4$	50	50-200	250	250
$GeCl_4$	0	0	0	964
$TiCl_4$	75	75-20	0	0
Chemical Flow (sccm)				
BCl_3	0	0-24	30	0

Constant Lathe Parameter

Spindle rotation - 60 rpm
Traverse speed - 15 cm/m
Oxygen flow added - 800 sccm
Temperature of chemicals - 28°C

Traverse delay (intake) - 5 sec
Traverse delay (exhaust) - 2 sec
Helium flow added - 400 sccm

Table 3-2. Preform Fabrication Parameters for the High Phosphorous Three-Layered Internally Deposited Compressive Cladded Fiber.

	Compressive Layers	Transition Layers	Cladding Layers	Transition Layers	Core Layers
No of Passes	26	5	90	2	15
Deposition Temperature (^{o}C)	1920	1920-1700	1575	1880	1900
Oxygen Flow thru bubblers (sccm)					
$SiCl_4$	50	75-175	200	200	200
$GeCl_4$	0	0	0	213-427	640
$POCl_3$	0	25-125	150	100-50	50
$TiCl_4$	75	0	0	0	0
Chemical Flow (sccm)					
BCl_3	0	0-21	27	14-7	0

<u>Constant Lathe Parameters</u>

Spindle rotation - 60 rpm
Traverse speed - 15 cm/m
Oxygen flow added - 800 sccm
Temperature of chemical - 28^{o}C

Traverse delay (intake) - 5 sec
Traverse delay (exhaust) - 2 sec
Helium flow added - 400 sccm

Table 3-3. Preform Fabrication Parameters for the Typical Four-Layered, Externally Deposited, Compressive Layer Fiber.

	Cladding Layer	Core Layer	Compressive Layer
No of Passes	90	15	∿12
Deposition Temperature (^{o}C)	1760	1930	1920
Traverse speed (cm/min)	15	15	8
Oxygen flow thru bubblers (sccm)			
$SiCl_4$	200	200	50
$GeCl_4$	0	640	0
$POCl_3$	75	50	0
$TiCl_4$	0	0	75-84
Chemical flow (sccm)			
BCL_3	75	50	0

Constant Lathe Parameter

Spindle rotation - 67 rpm
Temperature of chemicals - 28^{o}C

Traverse delay (intake) - 5 sec
Traverse delay (exhaust) - 2 sec

3.1.4 Exhaust System

An exhaust system on or about the lathe is necessary in order to properly remove the excess heat and spent process chemical which develops during the fabrication of the preform. Proper handling and/or treatment is necessary to keep the amount of exhausted doped silica soot and chlorine gases below the threshold limit value (TLV) set by the American Council of Government Industrial Hygienists (ACGIH).

3.1.5 Clean Area for Deposition Lathe

The area in which the glassworking lathe will be located should be kept as clean and dust free as possible in order to prevent degradation of the preform surface which may adversely affect the fiber strength and durability.

3.1.6 Chemical Etching Station

The station consists of an exhaust hood with a lamp and an etching tank. The facility must be capable of handling hydrofluoric acid. The etching tank provides a constant flow of acid over and around the immersed preforms. Details of the setup are shown in Figure 3-1.

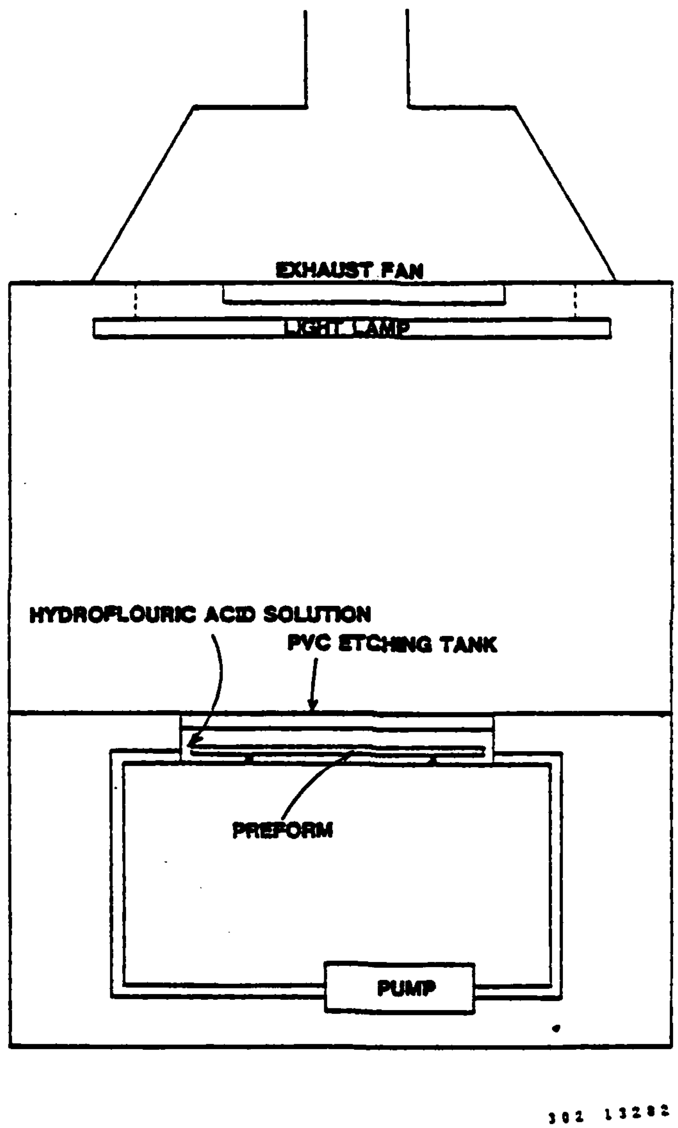


Figure 3-1. Chemical Etching Facilities.

Preforms shorter than 23 cm were usually etched in a magnetically stirred etching bath. The etching bath could simultaneously etch nine preforms at various temperatures and stirring rates. Details of the etch bath are shown in Figure 3-2.

3.1.7 Fiber Draw Tower

The equipment necessary to draw a preform into a high strength, long length optical fiber consists of the following components:

a. Down-feed system

b. H_2/O_2 torches

c. Diameter control device

d. Primary coating applicator

e. Curing oven

f. Drive capstan

g. Extruder

h. Proof tester

i. Spooler

A basic diagram of the draw tower is presented in Figure 3-3 which shows the equipment and the sequence in which it is used during the fabrication process.

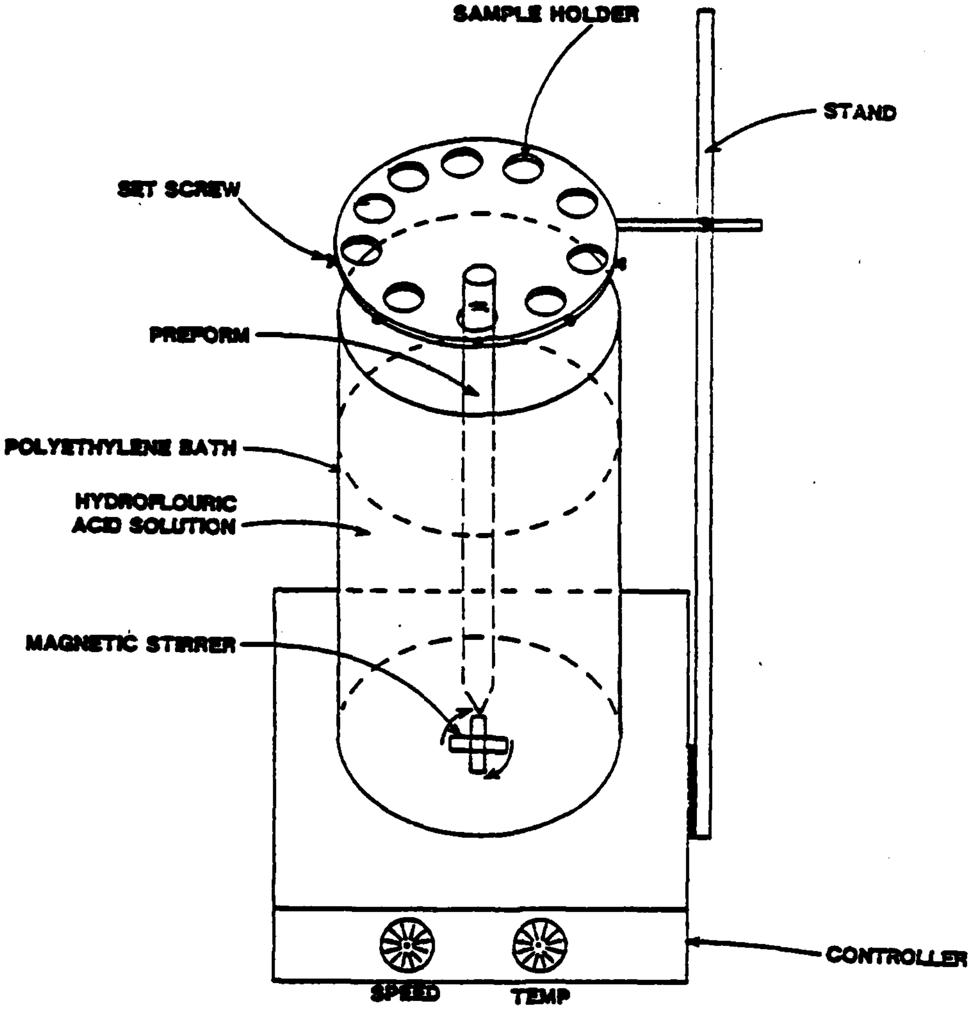


Figure 3-2. Chemical Etching Setup for Short Preforms.

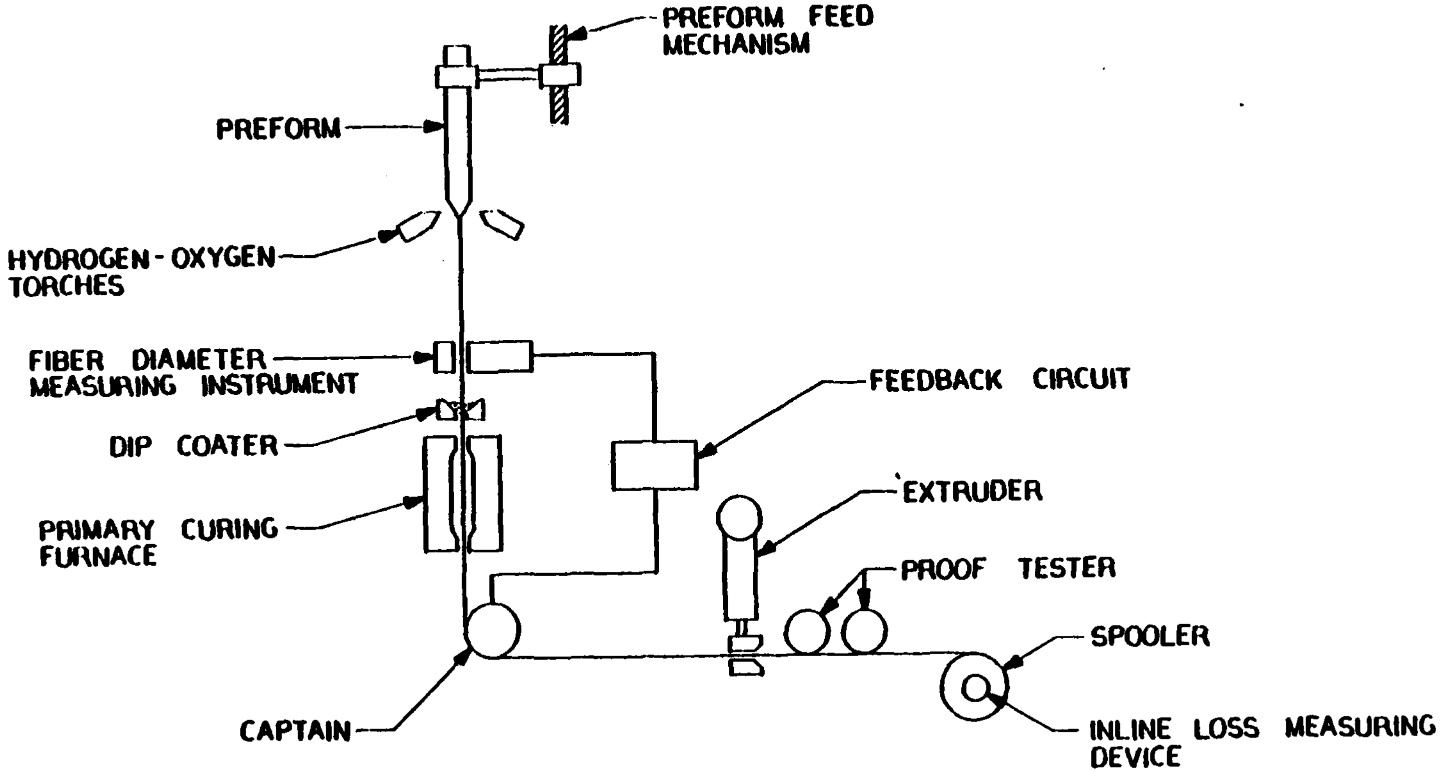


Figure 3-3. Optical Fiber Drawing Instrument Diagram.

3.1.7.1 Down-Feed System

This unit attaches to the preform at the butt end and lowers the preform into the flame at a constant rate to supply glass for the draw process. The feed rate should be between 0.3 and 0.8 cm/min with a linearity of ±0.5%.

3.1.7.2 Hydrogen Oxygen Torches

These torches must be mounted in the tower in such a way as to allow for x, y, and z positioning. The torches must also be capable of obtaining temperatures of 2000°C.

3.1.7.3 Diameter Control Device

This unit will measure the diameter of the fiber as it exits the flames. The unit supplies fiber diameter information via a feedback loop to the drive capstan. By precisely controlling the draw speed, the proper diameter of fiber is maintained. This entire system must be able to produce fibers of diameters of 125 μm ±4.0%. The detection window in this device should be sufficiently large to allow for some lateral motion of the fiber during draw (2 mm x 2 mm). The diameter sampling rate should be 1000 samples/s to allow for proper diameter measurement and control.

3.1.7.4 Primary Coating Applicator

The Applicator is a dipcoater in which the silicone RTV elastomer will be applied to provide a coating on the fiber. The applicator must be mounted in the tower to allow for on-line dipcoating of the fiber. The fiber must be thoroughly encapsulated by the silicone elastomer to an outer diameter of 12.5 mils ±2 mils (317 μm ±50 μm). After application the silicone elastomer is thermally cured.

3.1.7.5 Curing Oven

The primary coating thermal curing oven should be capable of maintaining a temperature of 500°C ±5°C. The curing oven should be located directly below the primary coating applicator to assure a uniform, well-cured coating. The curing oven should be 37" (94 cm) long for draw speeds up to 32 m/min.

3.1.7.6 Drive Capstan

The drive capstan provides the pulling force during fiber draw. It must be capable of maintaining no-slip contact with the fiber at all times without degrading the coating surface. The capstan must be able to attain draw speeds of 32 m/min with sufficient sensitivity and control to respond to the diameter monitoring device. The capstan should have both automatic and manual control capability.

3.1.7.7 Extruder

The extruder should develop sufficient pressure and temperature to extrude polyester elastomer materials on the optical fiber at diameters up to 20 mils (508 μm). The coating thickness is a nominal 4 mils (102 μm) over the primary coating. The extruder must be capable of applying the polyester elastomer in-line at a draw speed up to 32 m/min. The extruder must also be able to maintain the temperature specified in Table 3-4.

3.1.7.8 Proof Tester

The proof tester should be capable of providing an in-line proof stress level of 690 N/mm^2 (100 kpsi) on the fiber.

3.1.7.9 Spooler

The spooler should be capable of taking up fiber onto a spool at a rate equal to the draw speed and at low tension (50 grams or less).

Table 3-4. Extruder Setup and Draw Parameters.

Temperature in: neutral	Screens: stainless 35 mesh
Temperature out: °C	stainless 60 mesh
Zone 1: 200°C	stainless 80 mesh
Zone 2: 230°C	Material drier: 80°C
Zone 3: 232°C	Line speed: 32 m/min
Adapter: 235°C	Screw speed: 1.5 rpm
Die: 238°C	Screw set: 14
TIP inner diameter: 70 mils	Material use: 1.5 lb/h
TIP outer diameter: 100 mils	Motor amperage: 2.0
Die inner diameter: 230 mils	Melt temperature: 424°F
	Final outer diameter of fiber: 20.5 mils

3.1.8 Clean Room Facility for Fiber Draw Tower

The entire draw system should be kept as clean and dust free as possible. This prevents degradation in the strength of the fibers.

3.2 Materials

The following is a list of materials used in the fabrication of high strength, long length optical fibers:

a. Natural fused quartz tubing: 25-mm x 21.6-mm waveguide grade

b. Silicon tetrachloride: electronic grade - resistivity to be $\geq$200 ohm·cm

c. Germanium tetrachloride: electronic grade

d. Phosphorus oxychloride: 99.99% purity

e. Boron trichloride: 99.95% purity

f. Titanium tetrachloride: 99.95% purity

g. Oxygen: 99.99% purity

h. Helium: 99.995% purity

i. Hydrogen: bulk tank grade

j. Oxygen: bulk tank grade

k. Nitrogen: bulk tank grade

l. Natural fused quartz rod: 12-mm outer diameter (od)

m. Natural fused quartz tube: 36 mm x 32 mm

n. Natural fused quartz tube: 25 mm x 21.6 mm

o. Hydrofluoric acid: reagent grade

p. Nitric acid: reagent grade

q. Deionized water

r. Filtered dry air

s. Paraffin wax

t. Sylgard® 184 silicone RTV

u. Hytrel® 7246 polyester elastomer

3.3 Required Procedure and Operations

3.3.1 Cleaning of Glassware

The substrate tube must be cleaned to remove any impurities from the glass which can degrade both fiber strength and attenuation.

This operation is performed in the glass cleaning area with the necessary protective equipment being used by the operator. The substrate tube is placed in a bath of 50% hydrofluoric acid or rinsed with 50% hydrofluoric acid for 10 minutes to remove the outer layers of glass. Subsequently, a deionized water rinse is administered. The glass is then placed in a 40% nitric acid bath or rinsed with nitric acid for 10 minutes to remove other foreign materials. Again, a deionized water rinse is administered and, after this material is blown dry with filtered nitrogen. Proper precautions must be taken throughout the whole process to prevent scratching or recontaminating the glass.

3.3.2 Tube Mounting

In tube mounting, both the intake tube and substrate tubes are supported snugly in the lathe chucks in such a way that the unchucked ends are facing each other. Prior to sealing the intake and substrate tubes, the two pieces are straightened to ensure a proper joint. This process is done by starting from the lathe chuck and straightening towards the free end of each of the tubes. Afterwards, both ends are moved to approximately 1 mm apart, heated to their softening point, and then sealed. During this process it is important to keep a large flow (100 sccm/mm) of filtered gas (helium or nitrogen) moving through the tube to prevent dust particles from entering the tube during the sealing operation. It is also important that the tube's diameter be maintained throughout the sealing operation. Tube dimension can be maintained by control backpressure during the sealing operation.

The exhaust tube is straightened as described above but then tapered down using a torch and paddle until it matches the substrate tube diameter. It is then joined to the substrate using the aforementioned techniques.

3.3.3 Internal Deposition

Internal deposition is started immediately following a fire polishing pass. The proper chemical gas flows are set up and allowed to enter the substrate tube assembly while the traversing burner starts at the intake end of the tube. Depending on torch design, the flow rates of the hydrogen and oxygen are established using the deposition temperatures specified. These flows and temperatures are listed in Tables 3-1 through 3-3.

The glass layer that is deposited should be clear and free of bubbles. An oxyhydrogen hand torch should be placed so that its light flame is heating the sealed area on the exhaust tube. Also, a ribbon burner should be mounted along the entire length of the substrate. This assembly should be used from mid-cladding deposition to the end of the final collapse stage.

During deposition silica soot will build up in the exhaust tube. This soot must be removed to prevent preform contamination or clogging.

3.3.4 Collapse

Collapse is either a three- or four-pass operation depending upon the amount of open area remaining inside the tube after deposition. The collapse is performed in a traverse direction opposite to that of deposition.

The collapse takes place at temperatures of 2250°C with the deposition torch traversing at a rate of 1.5 cm/min or slower (depending on the open area). The lathe spindle rotates at 137 rpm and close attention should be given so that the consolidation of the tube is complete and bubble free. During the collapse a white film will develop on the outside of the preform. This film can be removed with subsequent acid treatment or fire polishing. Depending on the requirements of the draw tower feed system, the preform should be mounted to a section of support rod which is of a compatible length and diameter. During this mounting procedure a preform cane sample should be generated to check the preforms' properties.

3.3.5 Etching

The amount of silica to be removed from the preform will depend on the diameter of the preform and the depth to which etching is to be performed. This depth is usually determined by examining photographs of cross sections of canes drawn from the preform. The actual diameter of the preform is carefully measured at 1-cm intervals to determine the mean preform diameter. The target diameter, the diameter after chemical etching, is computed using the cane photograph and the mean diameter.

Before starting the etching process, the tip of the preform and the joint between the preform and the supporting rod is covered with hot paraffin wax. The preform is immersed in the etchant bath with acid. The frequency of preform inspections should increase as etching time increases.

After etching is finished the preform is removed and thoroughly washed and dried.

3.3.6 External Deposition

The T08 end of the etched preform is firmly attached into one of the lathe's chucks. A piece of T08 is placed in the other chuck, held firmly, and attached to the preform. To avoid contaminating the preform, straightening is performed in the T08 regions only.

The preform is then fire polished with the deposition torch mounted on the lathe's carriage traverse. Following the fire polishing procedure, the compressive layer is externally deposited under the parameters detailed in Table 3-3.

3.3.7 Mounting and Aligning Preform

The T08 butt end of the preform is clamped to the downfeed device. The preform is then aligned so that its axial centerline does not deviate more than 40 μm from the center line of the drawing process.

3.3.8 Preliminary Fiber Draw

The hydrogen/oxygen torch is ignited in a safe manner and the flow rate adjusted to obtain the 2000°C drawing temperature. After flames have been adjusted, the torch alignment should be checked with preform. This is accomplished by lowering the tip of the preform into the flame and adjusting x, y, and z position on torches until alignment is complete. The draw process is now ready to commence.

3.3.9 Fiber Draw Start Up

Set the preform down-feed speed at 0.35 cm/min and initiate the feed. Insert glass starting rod until contact with the preform is made. Slowly remove glass starting rod from the preform. The rod should have the small end of the preform attached with fiber trailing. Break the starting rod from the fiber and continue pulling the fiber manually. The fiber must then be passed through the dipcoater assembly, through the curing oven, and around a sheave. Adjust the x-y position of the dipcoater for a concentric coating. After adjusting the dipcoater, fill the dipcoater assembly with coating resin. When the fiber is coated, it can then be passed through the extruder. The extruder should be set up per Table 3-1. After the fiber has been passed through the extruder and the secondary coating applied, the fiber is then placed around the drive capstan. The diameter of the fiber is checked. Adjust the draw rate ($\sim$30 m/min) to obtain the desired fiber diameter. When the fiber diameter has been established, the fiber can be put on the proof tester wheel. Measure the proof test tension with the tension meter and adjust the tension to obtain the desired proof test level. String the fiber over the pulley system on the spooler dancer arm. The dancer controls spooling tension and may be adjusted as needed. Pass the fiber from the dancer onto the take-up spool and switch the spooler to "auto" to control spooling tension for the remainder of the draw.

3.3.10 Fiber Draw

Several times during draw, check the level of the coating material in the dipcoater, the diameter of the secondary coating, the proof test level, the spooler traverse, and the spooling tension.

3.4 Recommended Procedures and Operations

3.4.1 Chemical Handling

The chemicals used in these processes are of high purity and steps should be taken to ensure their quality. By placing in line filters on all gas cylinders the contamination due to cylinder changes will be reduced.

3.4.2 Maintenance of Glass Surface Quality.

The preform fabrication station should be located in a clean room to prevent contamination of the glass surface.

3.4.3 Fiber Draw Tower Room

It may be advantageous to have the entire draw process in a clean room. This should improve the strength characteristics of the drawn fiber.

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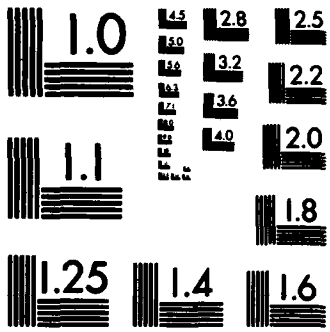

MICROCOPY RESOLUTION TEST CHART
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4.0 QUALITY ASSURANCE PROVISION

Preform qualities are ultimately determined through the fiber testing procedures outlined in the Prelimanary First Article Inspection Report submitted under this contract on February 13, 1980. However, some basic testing is undertaken prior to and following the fabrication of the preform to ensure good quality at this early stage of the process.

4.1 Responsibility for Inspection

Inspection of the preforms, components of the preforms, and vendors' lot analyses (which are supplied with materials) is the responsibility of the lathe operator. Standard laboratory procedures are required to inspect preform and glass components. High purity laboratory procedures are required to determine purity of materials and only used when necessary.

4.2 Monitoring Procedures for Equipment Used in the Process

The following is a list of routine maintenance and inspection items which should be previous to every fabrication start:

a. Fill $SiCl_4$ bubbler to a predetermined level prior to deposition of each run

b. Time traverse system and lathe spindle rpm and adjust if necessary to ensure reproducibility

c. Monitor chemical bubbler enclosure temperature and adjust to nominal figure

d. Clean rotary coupling filter and traversing burner torch tips to remove foreign matter

e. Check exhaust system to ensure that it is functional

During chemical etching the preform is routinely inspected for visible defects. Stress concentrations are detected by using polarized light. If the stress level becomes too acute the area of high stress is cut out of the preform using a oxyhydrogen torch.

Prior to the start of the draw process all equipment will be checked and calibrated to assure performance within specifications.

4.3 Monitoring Procedures for Materials

Materials used in the preform deposition area and fiber draw area are obtained to exact specifications and many are accompanied by a vendor's certification of analysis. All materials that can be checked by using simple laboratory practices will be inspected for compliance with specifications. All materials used will be stored and handled in such a manner as to not alter their characteristics.

4.4 Test Methods

Some basic tests are performed to check the preform quality prior to draw. Any preforms exhibiting properties other than those specified within a degree of error are not drawn into fibers. These tests are outlined in paragraphs 4.4.1 through 4.4.3.

4.4.1 Visual Inspection

The preform is thoroughly inspected for metal impurities on the preform surface and for bubbles included within the preform glass; observation of such defects requires the rejection of that preform portion.

4.4.2 Preform Diameter Ratios

A cane sample, pulled from the collapsed preform, is inspected under a microscope. A photograph of the cross-section of this cane is made and the diameters are measured to check for correct ratios.

4.4.3 Mechanical Test

All fibers are mechanically tested to assure that they meet contract specifications. Static fatigue, dynamic and bend testing, are performed. The first two tests are described in the Technical Proposal No R77-043 submitted by ITT Electro-Optical Products Division on November 1, 1977. The bend test is described in the Eighth Bimonthly Progress Report submitted by ITT Electro-Optical Products Division on April 12, 1980 under this contract.

5.0 NOTES

5.1 Intended Use

The intended use of this process is to produce a durable high strength, long length optical fiber. The durability of this fiber is enhanced by an outer compressive layer fabricated according to the process specification described herein.

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